Theory of pp/pA/small systems

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Flow in p-Pb is expected

- multiplicity as in peripheral A-A $\rightarrow$ large energy density
- sQGP observed in A-A
- $\eta/s = 0.08 \leftrightarrow$ mean free path $\simeq 0.2 - 0.3\text{fm} \ll$ size of the system
- size at freeze-out $\gg$ confinement scale
- collectivity *also* from preequilibrium flow
- large eccentricity

**smoking gun for collectivity**
Elliptic and triangular flow observed in p-Pb

- Glauber MC initial cond. - agreement with data

PB, W.Broniowski, G. Torrieri arXiv:1306.5442; G.Y. Qin, B. Müller 1306.3439; I. Kozlov et al. 1405.3976; A. Bzdak et al. 1304.34003, K. Kawaguchi et al. Poster 206

► $v_2$, $v_3$ consistent with hydro (Glauber MC, EPOS3)

► sensitive probe of init. cond.

$v_{2,3}$ - hydro response to initial deformation!

- EPOS3 - agreement with data

K. Werner et al. 1307.4379

- IP-Glasma initial cond. - small $v_2$, $v_3$!

B. Schenke, R. Venugopalan 1405.3605
Small system with large deformation

- deuteron projectile
  intrinsic deformation dominates over fluctuations → large $v_2$

- $^3$He projectile
  larger triangular flow

Nagle et al. arXiv:1312.4565

central collisions - deformed fireball, control of initial geometry
Elliptic and triangular flow in d-Au, $^3$He-Au and p-Au

PHENIX, arXiv:1507.06273

- observed $v_3$ → collectivity
- hierarchy of $v_2$ and $v_3$ consistent with collective response on fireball geometry

hydrodynamic calculations reproduce the data

sensitivity to details, limits of applicability of hydro - systematic model uncertainty

large eccentricity - large flow component
集体的反应对几何的响应

collective response to geometry
right magnitude and $k_\perp$ dependence of HBT radii
support collective scenario

Requires small intial fireball size
Collective flow in pp?

Collective like correlations observed in pp
\( V_n \) in optical Glauber + hydro(response)

\[
\begin{align*}
\frac{dN}{dy}(C) / (dN/dy)_{\text{max}} & \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1 \\
2v & \quad -0.04 \quad -0.02 \quad 0 \quad 0.02 \quad 0.04 \quad 0.06 \quad 0.08 \quad 0.1 \quad 0.12 \\
\text{pp Hard-sphere} & \quad \text{pp Fermi-I} & \quad \text{pp Fermi-II} & \quad \text{pp Exponential} & \quad \text{AuAu Fermi}
\end{align*}
\]

D’Enterria et al, 0910.3029

Habich et al. 1512.05354

- D’Enterria et al., 2009 ; hydro response, \( v_2 \approx 1\% \), wrong centrality dependence
- Luzumu, Romatschke, 2010 ; viscous hydro, \( v_2 < 2\% \) wrong centrality dependence
- Habich et al. 2015, ; viscous hydro, \( v_2 \approx 3 - 4\% \), wrong centrality dependence
\( v_n \) in fluctuating source + hydro(response)(...)

Werner, Karpenko, Pierog, 1011.0375

- Casalderrey-Solana, Wiedemann, 2010, Avsar et al. 2010, hot-spots (DIPSY) + hydro response, \( v_2 \simeq 6\% \), correct centrality dependence
- Werner et al., 2010, EPOS + hydro, ridge
- Deng et al. 2011, hot spots + parton cascade (BAMPS), large \( v_2 \geq 5\% \), \( v_3 \geq 1\% \)
- Bzdak et al. 2013, IP-Glasma+Hydro \( v_2 \simeq 2\% \)
- Ma, Bzdak, 2014, AMPT, ridge (semi-quantitative)

**Observed** \( v_n \) in pp are not in opposition to collective scenario
flow in small systems - what can we learn
mapping of space time distribution by flow - rapidity

sensitivity to fluctuations in energy deposition
event-plane decorrelation in p-Pb indicates the presence of longitudinal fluctuations - random flux tubes
flow in small systems - what can we learn
mapping of space time distribution by flow - transverse plane

Fireball size in p-Pb

PB, Broniowski, Rybczynski 1604.07697
- wounded quark model gives small fireball size
- compact source consistent with p-Pb data
(HBT, \( < p_{\perp} > \))

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p-p collisions (quark Glauber model)

- significant eccentricities in p-p
- small size of the interaction region 0.4fm
Hydrodynamics in small systems?

Hydrodynamics $K < 1$

1. Early stage, pressure asymmetry $P_L \ll P_\perp$

   - PHENIX Data Au-Au $s=200$ GeV
   - Charged particles $c=20-25$
   - $\tau_{iso}/2 \approx 0.25$ fm/c
   - $\tau_{eq}$

   - $P_0 \approx P_\perp$
   - $P_L(\tau_0) \approx (P_\perp/2) \approx 0.25$ fm/c

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   *H. Niemi, G. Denicol 1404.7327*

   *Early stage, pressure asymmetry - irrelevant*

2. Late stage, decoupling at freeze-out

   - early pressure asymmetry - irrelevant

   *H. Niemi, G. Denicol 1404.7327*

   *Late stage, decoupling at freeze-out*

   - A.Bzdak, G.L. Ma 1404.4129; L. He et al. 1502.05572

   *Late stage, decoupling at freeze-out*

   - hydrodynamics similar to AMPT cascade

   *Piotr Bożek Small systems*
SIGNS OF COLLECTIVITY IN SMALL SYSTEMS

1. **Elliptic and triangular flow**

2. **Hierarchy of $\nu_2$ and $\nu_3$ in p-A, d-A, He-A**
   collective response to geometry (final state effect)

3. **HBT radii**

+ ... 

- **Density driven** collective expansion
- **Hydrodynamics describes data for $p_\perp < 1.5\text{GeV}$**
- **Collectivity $\neq$ QGP ??**
Stronger flow in p-p?

Interferometry

Spectra

Y. Hirono, E. Shuryak 1412.0063

stronger transverse flow in p-p!

but: quantitative predictions for flow asymmetry
less robust in p-p, no smoking gun

K. Werner et al 1312.1233,
T. Kalaydzhyan, E. Shuryak 1503.05213

Hardening of spectra for high multiplicity events
flow in small systems - what can we learn

3. what flows?

medium probes in small systems: photons, jets, heavy flavors, balance functions

direct photons: S. Shen et al. 1504.07989
2) Flow from higher cumulants

- hierarchy of cumulants

\[ \epsilon_2\{4\} \simeq \epsilon_2\{6\} \simeq \epsilon_2\{8\} < \epsilon_2\{2\} \rightarrow \text{hydro response} \rightarrow v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\} < v_2\{2\} \]

- detailed hierarchy of cumulants - consistent with data

universal prediction for differences \( v_2\{4\} \neq v_2\{6\} \neq v_2\{8\} \)

\( v_2\{n\} \) - hydro response to fluctuations of initial shape!
$v_2\{4\}$ and $v_2\{2\}$ - hydro calculation

hierarchy $v_2\{2\} > v_2\{4\} > 0$ confirmed in full hydro calculation

also: I. Kozlov et al. 1412.3147

Note: $\epsilon_n + \text{hydro response} \rightarrow \text{correct centrality dependence of } v_n$
4) Factorization at intermediate $p_{\perp}$

- factorization holds for $v_2$ and $v_3$ up to 2.5 GeV
- small deviations explained by hydro+Glauber Kozlov, Luzum, Denicol, Jeon, Gale, 1405.3976

geometry driven origin of correlations at small and intermediate $p_{\perp}$
4b) Correlations at large $\Delta \eta$ (Ridge)

$^3$He-Au

\[ \text{a) Au side} \]

- PHENIX Data
- $-3.7 < \eta_{assoc} < -3.1$

\[ \text{b) $^3$He side} \]

- 3+1D Hydro
- $3.1 < \eta_{assoc} < 3.9$

$1 \text{GeV} < p_{T, \text{trig}} < 3 \text{GeV}, |\eta_{\text{trig}}| < 0.35$

\[ \Delta \phi \]

p-Pb

\[ \text{(b) } 90 \leq N_{\text{trk}} < 110, 1 < p_{T} < 3 \text{GeV} \]

\[ C(\Delta \eta, \Delta \phi) \]

PB, Broniowski 1211.0845

geometry driven origin of correlations at forward and backward rapidities