One fluid may not rule them all
- Collectivity in Pb-Pb, p-Pb and p-p collisions

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Various flow observables in large and small systems

ALICE, PRL 123, 142301 (2019)

ATLAS, PLB 789 (2019) 444

CMS, PLB 765 (2017) 193
<table>
<thead>
<tr>
<th>Observable or effect</th>
<th>Pb–Pb</th>
<th>p–Pb (high mult.)</th>
<th>pp (high mult.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $p_T$ spectra (“radial flow”)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Intermediate $p_T$ (“recombination”)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Statistical ratios</td>
<td>$\gamma_s^{GC} = 1, 10$–$30%$</td>
<td>$\gamma_s^{GC} \approx 1, 20$–$40%$</td>
<td>$\gamma_s^{C} &lt; 1, 20$–$40%$</td>
</tr>
<tr>
<td>Particle ratios</td>
<td>$\gamma_s^{GC} = 1, 10$–$30%$</td>
<td>$\gamma_s^{GC} \approx 1, 20$–$40%$</td>
<td>$\gamma_s^{C} &lt; 1, 20$–$40%$</td>
</tr>
<tr>
<td>HBT radii ($R(k_T), R(\sqrt{N_{ch}})$)</td>
<td>$R_{out}/R_{side} \approx 1$</td>
<td>$R_{out}/R_{side} \lesssim 1$</td>
<td>$R_{out}/R_{side} \lesssim 1$</td>
</tr>
<tr>
<td>Azimuthal anisotropy ($v_n$) (from two particle correlations)</td>
<td>$v_1$–$v_7$</td>
<td>$v_1$–$v_5$</td>
<td>$v_2$–$v_4$</td>
</tr>
<tr>
<td>Characteristic mass dependence</td>
<td>$v_2$–$v_5$</td>
<td>$v_2$, $v_3$</td>
<td>$v_2$</td>
</tr>
<tr>
<td>Directed flow (from spectators)</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Charge-dependent correlations</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Higher-order cumulants</td>
<td>“$4 \approx 6 \approx 8 \approx LYZ$” +higher harmonics</td>
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<td>“$4 \approx 6$”</td>
</tr>
<tr>
<td>Symmetric cumulants</td>
<td>up to SC(5, 3)</td>
<td>only SC(4, 2), SC(3, 2)</td>
<td>only SC(4, 2), SC(3, 2)</td>
</tr>
<tr>
<td>Non-linear flow modes</td>
<td>up to $v_6$</td>
<td>not measured</td>
<td>not measured</td>
</tr>
<tr>
<td>Weak $\eta$ dependence</td>
<td>yes</td>
<td>yes</td>
<td>not measured</td>
</tr>
<tr>
<td>Factorization breaking</td>
<td>yes ($n = 2, 3$)</td>
<td>yes ($n = 2, 3$)</td>
<td>not measured</td>
</tr>
<tr>
<td>Event-by-event $v_n$ distributions</td>
<td>$n = 2$–$4$</td>
<td>not measured</td>
<td>not measured</td>
</tr>
<tr>
<td>Direct photons at low $p_T$</td>
<td>yes</td>
<td>not measured</td>
<td>not observed</td>
</tr>
<tr>
<td>Jet quenching through dijet asymmetry</td>
<td>yes</td>
<td>not observed</td>
<td>not observed</td>
</tr>
<tr>
<td>Jet quenching through $R_{AA}$</td>
<td>yes</td>
<td>not observed</td>
<td>not observed</td>
</tr>
<tr>
<td>Jet quenching through correlations</td>
<td>yes ($Z$–jet, $\gamma$–jet, $h$–jet)</td>
<td>not observed ($h$–jet)</td>
<td>not measured</td>
</tr>
<tr>
<td>Heavy flavor anisotropy</td>
<td>yes</td>
<td>yes</td>
<td>not measured</td>
</tr>
<tr>
<td>Quarkonia production</td>
<td>suppressed$^\dagger$</td>
<td>suppressed</td>
<td>not measured</td>
</tr>
</tbody>
</table>
One fluid rules all – early work

One fluid to rule them all: Viscous hydrodynamic description of event-by-event central $p+p$, $p+Pb$ and $Pb+Pb$ collisions at $\sqrt{s} = 5.02$ TeV

Ryan D. Weller\textsuperscript{a}, Paul Romatschke\textsuperscript{a,b,*}  

superSONIC for $p+p$, $\sqrt{s}=5.02$ TeV, 0-1%  
superSONIC for $p+Pb$, $\sqrt{s}=5.02$ TeV, 0-5%  
superSONIC for $Pb+Pb$, $\sqrt{s}=5.02$ TeV, 0-5%

- superSONIC describes $v_2$ and $v_3$ data in $p+p$, $p+Pb$ and $Pb+Pb$ using a single choice for the fluid parameter
- Suggests \textit{common hydrodynamic origin} including \textit{pp} collisions
Can one fluid rules them all? 
-a detailed evaluations from hydrodynamics

Brief review for Pb-Pb, p-Pb collisions
-Success of hydrodynamics (Pb-Pb)
-hydro descriptions; initial /final state effects (p-Pb)

Pb+Pb, p-Pb, p-p collisions
-can one hydrodynamics (with the same parameters) rules them all?

p-p collisions
-sign of C2{4} & non-linear effect from hydrodynamics
Can one fluid rules them all?
-a detailed evaluations from hydrodynamics

Brief review for Pb-Pb, p-Pb collisions

Success of hydrodynamics (Pb-Pb)
The Success of Hydrodynamics in Pb+Pb collisions

Hydro + IP-Glasma
Gale, et. Al, PRL2013

iEBE-VISHNU + AMPT
Xu, Li, Song, PRC 2016

-hydrodynamics nice describe of integrated and differential $V_n$ of all charged and identified hadrons
The Success of Hydrodynamics in Pb+Pb collisions (II)

Flow distributions

**ALICE**: 1912.00740.

Non-Linear flow modes

Hydro calculations / predictions:

Hydro output + coalescence model predictions:

V2, V3 for deuterons

**ALICE**: PRC102 055203 (2020).

Hydro quantitatively / qualitatively describe / predict various flow data for Pb+Pb collisions
An quantitatively extraction of the QGP viscosity

- An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation
- $\eta/s(T)$ is very close to the KSS bound of $1/4\pi$

Can one fluid rules them all?
- a detailed evaluations from hydrodynamics

**Brief review for Pb-Pb, p-Pb collisions**
- Success of hydrodynamics (Pb-Pb)
- hydro descriptions; initial /final state effects (p-Pb)

**Pb+Pb, p-Pb, p-p collisions**
- can one hydrodynamics (fluid) rules them all?

**p-p collisions**
- sign of C2{4} & non-linear effect from hydrodynamics
Flow in p-Pb -- Hydrodynamics Simulations

in p+Pb collisions at 5.02 TeV

P. Bozek, W. Broniowski, G. Torrieri, PRL2013

G.-Y. Qin, B. Muller, PRC2014

K. Werner, et. Al., PRL2014
Initial state or Final state effects?

**Initial state effects:**
- B. Schenke, S. Schlichting, P. Tribedy, and R. Venugopalan, PRL2016

... ... ... ...

**Final state interactions:**
- P. Bozek, W. Broniowski, G. Torrieri, PRL2013
- G.-Y. Qin, B. Muller. PRC2014
- Y. Zhou, X. Zhu, P. Li, and H. Song, PRC2015
- P. Bozek, A. Bzdak, and G.-L. Ma, PLB2015

... ... ... ...
Can one fluid rule them all?

- a detailed evaluations from hydrodynamics

Brief review for Pb-Pb, p-Pb collisions

- Success of hydrodynamics (Pb-Pb)
- hydro descriptions; initial / final state effects (p-Pb)

Pb+Pb, p-Pb, p-p collisions

- can one hydrodynamics with the same parameters rule them all?

p-p collisions

- sign of C2\{4\} & non-linear effect from hydrodynamics
Hydrodynamic simulations (iEBE-VISHNU + TRENTo) nicely fit the $P_T$ spectra and $<P_T>$ for Pb-Pb, p-Pb and p-p collisions with the same parameter set.


-PKU parameter: (smaller fluctuations) Fu, Zhao & Song, in preparation
Hydrodynamic simulations (iEFE-VISHNU + TRENTo) with both Duke Bayesian parameter / PKU tuned parameter roughly fit $v_2$ $v_3$ measured from 2 particle correlations.

Fu, Zhao & Song, in preparation
Hydrodynamic simulations (iEBE-VISHNU + TRENTo) with both Duke / PKU parameters fails to reproduce negative $c_2 \{4\}$.

One fluid rule can not them (Pb-Pb, p-Pb, p-p) all sings problem of $c_2 \{4\}$ in p-p collisions.

Fu, Zhao & Song, in preparation
Can one fluid rules them all?
-a detailed evaluations from hydrodynamics

Brief review for Pb-Pb, p-Pb collisions
-Success of hydrodynamics (Pb-Pb)
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Pb+Pb, p-Pb, p-p collisions
-can one hydrodynamics (fluid) rules them all?

p-p collisions
-sign problem of C_{2\{4\}} & non-linear effect from hydrodynamics
Different initial conditions


-Different $p(\varepsilon_2)$ distributions with positive and negative $C_2^{\varepsilon}\{4\}$
Hydrodynamics with different initial conditions could roughly describe $v_2$ & $v_3$

Hydro simulations with various initial conditions fails to reproduce negative $C_2\{4\}$

The sign problem of \( C_2^\{4\} \) can not describe negative \( c_2^\{4\} \).

-MUSIC with IP-glasma also give positive \( c_2^\{4\} \) in pp collisions.

Zhao, Zhou & Song, in preparation.
P\(\langle v_2 \rangle\) and P\(\langle \varepsilon_2 \rangle\) distributions: from \(C^\varepsilon_2\{4\}\) to \(C^v_2\{4\}\)

-Cubic response: \(|v_2| = 0.115|\varepsilon_2| + 0.080|\varepsilon_2|^3\)

-Certain deviations between P\(\langle v_2/\langle v_2 \rangle \rangle\) and P\(\langle \varepsilon_2/\langle \varepsilon_2 \rangle \rangle\)

Leading small negative \(C^\varepsilon_2\{4\}\) change to small positive \(C^v_2\{4\}\)

Such sign problem of \(c_2\{4\}\) in p-p collisions is natural for hydro simulations.
Can one fluid rules them all?  
-a detailed evaluations from hydrodynamics

\[ \text{Pb+Pb, } p-\text{Pb, } p-p \text{ collisions} \]
-can one hydrodynamics (fluid) rules them all?

\[ \text{p-p collisions} \]
-sign problem of C2{4} \& non-linear effect from hydrodynamics

Is QGP formed in the small systems?  
\( (p-\text{Pb collisions}) \)
Reminder: QGP signals in large systems

Au+Au / Pb+Pb

QGP was discovered @RHIC & LHC

- strong elliptic flow
- jet quenching
- NCQ scaling of elliptic flow
NCQ scaling of $v_2$ in $p$-Pb collisions (EXP)

- An observation of the approximately NCQ scaling at intermediate $p_T$ in high multiplicity events of $p$-Pb collision in data.
- Is it an indication of the partonic degree of freedom?
Hydro-Coal-Frag Hybrid Model

**Thermal hadrons (VISH2+1):**
- generated by hydro.
  with Cooper-Frye.
  Meson: $P_T < 2P_1$; baryon: $P_T < 3P_1$.

**Coalescence hadrons (Coal Model):**
- generated by coalescences model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

**Fragmentation hadrons (LBT):**
- the remnant hard quarks feed to fragmentation.

**UrQMD afterburner:**
- All hadrons are feed into UrQMD for hadronic evolution, scatterings and decays.

Zhao, Ko, Liu, Qin & Song, Phys. Rev. Lett. 125 7 072301 (2020)
Our combined model, Hydro-Coal-Frag, gives a nice description of spectra of pion, kaon and proton as well as the $P/\pi$ over $p_T$ from 0 to 6 GeV.
v2(pT) and NCQ scaling

- Hydro-Coal-Frag model gives a nice description of v2(pT) of pion, kaon and proton over pT from 0 to 6 GeV.

- At intermediate pT, Hydro-Coal-Frag model can obtain an approximate NCQ scaling as shown by the data.

Strongly indication of partonic degree of freedom in small system.

Without coalescence, Hydro-Frag largely underestimates the $v_2(p_T)$ at intermediate $p_T$, violating the NCQ Scaling of $v_2$.

The importance of quark coalescence in $p$-$Pb$ collisions

Strongly indication of partonic degree of freedom in small system!

Zhao, Ko, Liu, Qin & Song, Phys. Rev. Lett. 125 7 072301 (2020)
Summary

-Can one fluid rule them all (Pb-Pb, p-Pb, p-p collisions) ?

**NO !**

Hydro simulations with various initial conditions **fails to reproduce negative C2{4} in p-p collisions**, due to non-linear response.

-Is QGP formed in the small systems (p-Pb collisions)?

Hydro-Coal-Frag calculations (Coalescence mechanism) nicely described NCQ scaling of v2 at mediate pT,

**strongly hint partonic degrees of freedom in high multiplicity p-Pb collisions**
Due to non flow effects, $c_2\{4\}$ obtained by standard method strongly depend on $N_{ch}^{sel}$, even reversing the sign.

3 subevent cumulant can largely suppress the non-flow effects.

$C_2\{4\}$ obtained by 3-subevent weakly depend on $N_{ch}^{sel}$ at larger $\langle N_{ch} \rangle$.

\[
\langle \langle 4 \rangle \rangle_{3\text{sub}} = \langle \langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle \rangle
\]

\[
\langle \langle 2 \rangle \rangle_{3\text{sub}}^2 = \langle \langle \cos n(\varphi_1 - \varphi_3) \rangle \rangle \langle \langle \cos n(\varphi_2 - \varphi_4) \rangle \rangle
\]

\[
c_n\{4\}_{3\text{sub}} = \langle \langle 4 \rangle \rangle_{3\text{sub}} - 2 \cdot \langle \langle 2 \rangle \rangle_{3\text{sub}}^2
\]
More details on $C_2\{4\}$ calculations

**Minimize multiplicity fluctuations**: (same method as used by ATLAS)

1) Cut the multiplicity class with $N_{ch}^{sel}$ within $0.3 < p_T < 3.0$ GeV, $|\eta| < 2.4$, calculate $c_2\{2\}$ & $c_2\{4\}$ for events with the same $N_{ch}^{sel}$ to minimize multiplicity fluctuation.

2) Combined $c_2\{2\}$ & $c_2\{4\}$ of several $N_{ch}^{sel}$ for the event ensemble.

3) Map the $N_{ch}^{sel}$ to the common event activity measure $N_{ch}$ with $p_T > 0.4$ GeV, $|\eta| < 2.4$ to compare with experiment data

![Graph showing $C_2\{4\}$ for different methods and pT ranges.](image.png)

In iEBE-VISHNU, no jets, non-flow mainly from resonance decays, standard method gives same results as 2- and 3- subevent methods.

**Thermal & hard Partons:**

- Thermal partons generated by hydro
- Hard partons generated by PYTHIA8, then suffered with energy loss by LBT

### Coalescence processes:

- thermal - thermal parton coalescence
- thermal - hard parton coalescence
- hard - hard parton coalescence

**Coalescence model**

\[
\frac{dN_M}{d^3p_M} = g_M \int d^3x_1 d^3p_1 d^3x_2 d^3p_2 f_q(x_1, p_1) f_{\bar{q}}(x_2, p_2) \times W_M(y, k) \delta^{(3)}(p_M - p_1 - p_2)
\]

\[
\frac{dN_B}{d^3p_B} = g_B \int d^3x_1 d^3p_1 d^3x_2 d^3p_2 d^3x_3 d^3p_3 f_{q_1}(x_1, p_1)
\]

\[
\times f_{q_2}(x_2, p_2) f_{q_3}(x_3, p_3) W_B(y_1, k_1; y_2, k_2) \times \delta^{(3)}(p_B - p_1 - p_2 - p_3)
\]
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Zhao, Ko, Liu, Qin & Song,
**$v_2(P_T)$ from hydro or fragmentation alone**

$p + \text{Pb} @ \sqrt{s_{NN}} = 5.02 \text{ TeV}, 0-20\%$

Hydro or fragmentation alone cannot describe $v_2(P_T)$ in high multiplicity p-Pb collisions.