Do we produce quark-gluon plasma in all colliding systems?

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Parallel session: Deconfinement
01/08/18
Brief outline of this talk content...

Studying the phase diagram of nuclear matter
- Phase transition(s)
- Properties of quark-gluon plasma
Brief outline of this talk content...

**Studying the phase diagram of nuclear matter**
- Phase transition(s)
- Properties of quark-gluon plasma

**QGP properties:**
- Perfect fluid
- In-medium interaction
Brief outline of this talk content...

Studying the phase diagram of nuclear matter
- Phase transition(s)
- Properties of quark-gluon plasma

QGP properties:
- Perfect fluid
- In-medium interaction

Onset of deconfinement
- Low density and high T: heavy ion collisions
  - Large system
- Do we produce QGP in smaller systems
  - pp, p-A, ...
Brief outline of this talk content...

1- What we know from AA

2- What we have learnt from small systems

3- Conclusion and prospective
Heavy Ion collisions

Taken from: https://goo.gl/2Ekbru
Heavy Ion collisions

Taken from: https://goo.gl/2Ekbru

Hydrodynamic evolution
Perfect fluid paradigm

Initial state

\[ \varepsilon(x, y, \eta^s) \]
Do we produce QGP in all hadronic colliding systems?

- Maxime Guilbaud

**Perfect fluid paradigm**

**Initial state**

**Event by Event**

- Pre-equilibrium

\[ \delta_\mu T^{\mu\nu} = 0 + (\eta, \zeta, ...) \]

- Hydrodynamics

- Freeze-out

Hadronic transport

QGP behave like a nearly perfect fluid

(small \( \eta/s \))
Perfect fluid paradigm

Initial state

Event by Event

Final state

QGP behave like a nearly perfect fluid (small $\eta/s$)

Pre-equilibrium

Hydrodynamics

$\delta_{\mu} T^{\mu\nu} = 0 + (\eta, \zeta, \ldots)$

Freeze-out
Hadronic transport

$f(p_T, \eta, \phi)$

$V_2$
Perfect fluid paradigm

**Initial state**

**Event by Event**

**Final state**

- **Pre-equilibrium**
  - Hydrodynamics: \( \delta_{\mu} T^{\mu\nu} = 0 + (\eta, \zeta, ...) \)

- **Freeze-out**
- **Hadronic transport**

**QGP behave like a nearly perfect fluid**
(small \( \eta/s \))

**Fourier bases:**

\[
 f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \vec{V}_n(p_T, \eta) e^{-i n \phi}
\]

**Anisotropic flow**

\[
 \vec{V}_n = v_n e^{in\Psi_n}
\]
What does this flow harmonic coefficients means?

Initial-state anisotropy

Flow ≈ Geometry

Final state:

\[ f(p_T, \phi, \eta) \sim 1 + 2v_2(p_T, \eta) \cos [2(\phi - \Psi_2)] \]
What does this flow harmonic coefficients mean?

Initial-state anisotropy

Flow ≈ Geometry

Initial-state inhomogeneity

$\Psi_{EP}$: Direction of maximum particle density

Final state:

$f(p_T, \phi, \eta) \sim 1 + 2v_2(p_T, \eta)\cos [2(\phi - \Psi_2)]$
What does this flow harmonic coefficients mean?

Initial-state anisotropy

Initial-state inhomogeneity

Flow

≈

Geometry

+

Fluctuations

\( \Psi_{EP} \): Direction of maximum particle density

Final state:

\[
f(p_T, \phi, \eta) \sim 1 + 2v_2(p_T, \eta) \cos [2(\phi - \Psi_2)] + 2v_3(p_T, \eta) \cos [3(\phi - \Psi_3)]
\]

Triangular flow
What does this flow harmonic coefficients mean?

Flow

≈

Geometry

+

Fluctuations

$\Psi_{EP}$: Direction of maximum particle density

Final state:

\[
f(p_T, \phi, \eta) \sim 1 + 2v_2(p_T, \eta)\cos[2(\phi - \Psi_2)] + 2v_3(p_T, \eta)\cos[3(\phi - \Psi_3)] + 2v_4(p_T, \eta)\cos[4(\phi - \Psi_4)] + 2v_5(p_T, \eta)\cos[5(\phi - \Psi_5)] + \ldots
\]
What does this flow harmonic coefficients mean?

In AA, Rather good understanding of:
- Initial state geometry
- Initial state fluctuations
- Medium transport coefficients ($\eta/s$, ...)

CMS results

Phys. Rev. C 89, 0449076

Phys. Rev. Lett. 110, 012302

IP glasma + MUSIC
How do we measure this flow coefficients in AA?

Particle 1
(\eta_1, \varphi_1)

Δ\eta = \eta_1 - \eta_2
Δ\varphi = \varphi_1 - \varphi_2

Particle 2
(\eta_2, \varphi_2)
How do we measure this flow coefficients in AA?

Particle 1
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\Delta \eta = \eta_1 - \eta_2
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Particle 2
(\eta_2, \varphi_2)

Single jet contribution
How do we measure this flow coefficients in AA?

Particle 1
($\eta_1, \varphi_1$)

$$\Delta \eta = \eta_1 - \eta_2$$
$$\Delta \varphi = \varphi_1 - \varphi_2$$

Particle 2
($\eta_2, \varphi_2$)

Single jet contribution + Back-to-back jet contribution
How do we measure this flow coefficients in AA?

Particle 1
$(\eta_1, \varphi_1)$

$\Delta \eta = \eta_1 - \eta_2$
$\Delta \varphi = \varphi_1 - \varphi_2$

Particle 2
$(\eta_2, \varphi_2)$

Single jet contribution
Back-to-back jet contribution
Collective effect
How do we measure this flow coefficients in AA?

2 particle correlations $v_2\{2\}$

Corrections applied

Single jet contribution

Back-to-back jet contribution

Collective effect

PhysLetB.2016.12, 009
Study collectivity using multi-particle measurements

- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events

\[
\langle 4 \rangle = \frac{1}{P_{M,4}} \sum_{i,j,k,l} e^{i n(\phi_i + \phi_j - \phi_k - \phi_l)},
\]

\[
P_{M,4} = \frac{M!}{4!(M-4)!}
\]

\[
c_n{\{4\}} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2,
\]

\[
v_n\{4\} = \sqrt[4]{-c_n\{4\}}
\]
Study collectivity using multi-particle measurements

6 particle correlations

\[ v_2\{6\} \]

- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events

\[ v_n\{6\} = \sqrt{\frac{1}{4} c_n\{6\}} \]

Preliminary CMS

01/08/18

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PhysLettB.2016.12, 009
Study collectivity using multi-particle measurements

8 particle correlations

\[ v_2\{8\} \]

- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events

\[ v_n\{8\} = \sqrt{\frac{1}{33} c_n\{8\}} \]

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PhysLetB.2016.12, 009

01/08/18

Do we produce QGP in all hadronic colliding systems? – Maxime Guilbaud
Study collectivity using multi-particle measurements

- Less sensitive to non-flow (i.e. jet induced correlation)
- Needs larger sample of events

Collectivity: $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\text{LYZ}\}$

Well describe by **hydrodynamic** at low $p_T$ ($< 3 \text{ GeV/c}$)

PhysLettB.2016.12, 009
Small system puzzle

Hydro behavior in A-A:

- Long-range correlation (Ridge)
- Collective behavior

(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 < N_{\text{trk}}^{\text{ offline}} < 260$
- $1 < p_{T}^{\text{trig}} < 3$ GeV/c
- $1 < p_{T}^{\text{assoc}} < 3$ GeV/c

Pb-Pb

PLB (2013) 06, 028
Small system puzzle

Hydro behavior in A-A:
- Long-range correlation (Ridge)
- Collective behavior

Ridge observed in small systems

PLB (2013) 06, 028

Pb-Pb

PRL (2018) 120, 092301

Do we produce QGP in all hadronic colliding systems? – Maxime Guilbaud
Ridge tsunami at LHC and RHIC

Ridge observation at various energies and for very different system sizes
Measurement of $v_n$ coefficients

- Collectivity: $v_2^2 \geq v_2^4 \approx v_2^6 \approx v_2^8 \approx v_2^{LYZ}$

**PbPb $\sqrt{s_{NN}} = 2.76$ TeV**

$0.3 < p_T < 3.0$ GeV/c

$|\eta| < 2.4$

$N_{\text{trk}}^{\text{offline}}$

**PhysLettB.2016.12, 009**
Measurement of \( v_n \) coefficients

- Collectivity: \( v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \)

\[ \text{physlettB.2016.12, 009} \]
Measurement of $v_n$ coefficients

- Collectivity: $v_2^2 \approx v_2^4 \approx v_2^6$

What do we learn here?
Data interpretation: 2 scenarii

Observed long-range correlations in $\eta$

Rooted in initial/early stage

$$\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right) \sim 0.1 \text{ fm/c}$$

Initial spatial $\varepsilon_s$  + final interactions

arXiv:1509.07939
Data interpretation: 2 scenarii

Observed long-range correlations in $\eta$

Rooted in initial/early stage

$$\tau_o \leq \tau_{F.O.} \exp\left( -\frac{1}{2} |y_a - y_b| \right) \sim 0.1 \text{ fm/c}$$

Initial spatial $\varepsilon_s$

+ final interactions

Initial spatial $\varepsilon_p$

by initial interactions

arXiv:1509.07939
Data interpretation: 2 scenarii

Observed long-range correlations in $\eta$

Rooted in initial/early stage

$$\tau_0 \leq \tau_{F.O.} \exp\left(-\frac{1}{2}\left|y_a - y_b\right|\right) \sim 0.1 \text{ fm/c}$$

Scenario #1

Initial spatial $\varepsilon_s$ + final interactions

Hydrodynamics
Parton transport, escape

Scenario #2

Initial spatial $\varepsilon_p$ by initial interactions

CGC Glasma
Color-field domains, etc.
Comparison with different scenarii...

- First try from PHENIX to differentiate scenarii
  - Seems to favor hydro-like description
- Nevertheless, quick answer from IS model (color domains) appeared showing similar feature

arXiv:1805.029773
Comparison with different scenarii...

- First try from PHENIX to differentiate scenarii
  - Seems to favor hydro-like description
- Nevertheless, quick answer from IS model (color domains) showed showing similar feature

arXiv:1805.02977

NOT ENOUGH TO CONCLUDE! MORE DETAILS NEEDED
Correlation between harmonics

Study correlation between harmonics (n,m)

- Via Symmetric Cumulants (SC) \[ SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \]
- Based on 4-particle cumulant calculations

Sensitive to:

- IS fluctuations
- Medium transport coefficient
Correlation between harmonics

Study correlation between harmonics \((n,m)\)

- Via **Symmetric Cumulants (SC)** \[ SC(n, m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \]
- Based on 4-particle cumulant calculations

**Sensitive to:**
- IS fluctuations
- Medium transport coefficient

**Results in Pb-Pb:**

- **SC(2,4):** \(v_2, v_4\) correlated
- **SC(2,3):** \(v_2, v_3\) anti-correlated

*Figure showing correlation plots for different systems and channels.*
The small system case

Similarities observed for SCs in all systems

- \((v_2, v_3)\) uncorrelated
- \((v_2, v_4)\) correlated
- Small energy dependence (see p-Pb results)

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In general, \(v_n(p-p) \neq v_n(p-Pb) \neq v_n(Pb-Pb)\)

Normalization needed for comparison

PRL (2018)120, 092301

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The small system case

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PRL (2018)120, 092301

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PRL (2018) 120, 092301
Similar behavior in p-Pb and Pb-Pb
Points to similar IS fluctuations

Common paradigm?
Normalized SC (NSC)

- Similar behavior in p-Pb and Pb-Pb
- Points to similar IS fluctuations

Common paradigm?

- Ordering observed: p-p > p-Pb > Pb-Pb

What is the origin?
Do we produce QGP in all hadronic colliding systems? – Maxime Guilbaud

Similar behavior in p-Pb and Pb-Pb

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What is the origin?
Do we produce QGP in all hadronic colliding systems? – Maxime Guilbaud

Similar behavior in p-Pb and Pb-Pb
Points to similar IS fluctuations

Can be:
• ≠ transport coefficients
• Remaining non-flow
• ...

Ordering observed:
p-p > p-Pb > Pb-Pb

Common paradigm?

What is the origin?
Normalized SC (NSC)

CMS

Need of further non-flow suppression!

CMS

0.3 < p_T < 3 GeV/c

○ Similar behavior in p-Pb and Pb-Pb
○ Points to similar IS fluctuations

Common paradigm?

○ Ordering observed:
  p-p > p-Pb > Pb-Pb

What is the origin?
How to suppress non-flow?

Method:
- PRC (2017) 84, 044911
- PRC (2017) 96, 034906
- PLB (2018) 777, 201

Concept: Suppressing non-flow contribution with subevents

No sub-evt
1, 2, 3, 4

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Do we produce QGP in all hadronic colliding systems? – Maxime Guilbaud
How to suppress non-flow?


Concept: Suppressing non-flow contribution with subevents

| No sub-evt | 1, 2, 3, 4 |
| 2 sub-evt | 1, 2 | 3, 4 |

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How to suppress non-flow?

**Method:**
- PRC (2017) 84, 044911
- PRC (2017) 96, 034906
- PLB (2018) 777, 201

**Concept:** Suppressing non-flow contribution with subevents

```
no sub-evt
1, 2, 3, 4

2 sub-evt
1, 2
3, 4

3 sub-evt
1
2, 3
4
```

Larger suppression of non-flow contribution using more subevents
SCs with subevents

\[ 0.3 < p_T < 3 \text{ GeV/c} \]

\[ N_{\text{offline}} \]
SCs with subevents

- Non-flow suppressed at low-multiplicities

**CMS Preliminary**

0.3 < $p_T$ < 3 GeV/c

CMS-­‐PAS-­‐HIN-­‐18-­‐015
SCs with subevents

CMS Preliminary

\[ N_{\text{trk}}^{\text{offline}} \]

- Non-flow suppressed at low-multiplicities
- Similar results at high multiplicities for SC(2,3)

CMS-PAS-HIN-18-015
SCs with subevents

Do we produce QGP in all hadronic colliding systems? – Maxime Guilbaud
SCs with subevents

- Non-flow suppressed at low-multiplicities
- Similar results at high multiplicities for SC(2,3)
- Different results between no- and n-subevents at high-multiplicities for SC(2,4)

Do we produce QGP in all hadronic colliding systems? – Maxime Guilbaud
Zooming to the high multiplicity region

- **SC(2,3):** Negligible contribution from non-flow
- **SC(2,4):** Remaining contribution of non-flow in the no-subevent case?

**CMS-PAS-HIN-18-015**
Do we produce QGP in all hadronic colliding systems? – Maxime Guilbaud

Zooming to the high multiplicity region

CMS PAS-HIN-18-015

- SC(2,3): Negligible contribution from non-flow
- SC(2,4): Remaining contribution of non-flow in the no-subevent case?
  - Difference among subevent results observed: unexpected ordering!
What did we learn? An emerging common paradigm

Similar effects are observed in all hadronic colliding systems

- The effect is clearly collective: 2 scenarii available

- There are hints of an emerging common paradigm
What did we learn? An emerging common paradigm

Similar effects are observed in all hadronic colliding systems

- The effect is clearly collective: 2 scenarii available

- There are hints of an emerging common paradigm

Too early to conclude, more data and quantitative theoretical prediction are needed
What did we learn? Geometry and fluctuation of IS at the collisions

In small systems, fluctuations matters

- For example, small systems results can probe proton sub-nucleonic fluctuations
- Better understanding of IS in small systems will help to understand large ones
Emergence of hot QCD phenomena in small colliding systems

- Standard descriptions of pp and AA physics may lack ingredients
- We are missing one big part to claim for a QGP!

Where are the interactions with the medium?

Where is the onset of deconfinement?

- What are the least ingredients needed to reach deconfinement?
- No observation in electron-positron collisions so far