Experimental overview of collective flow with identified particles at RHIC and the LHC

Panos Christakoglou (Nikhef)
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Many thanks to the (flow) groups from PHENIX, STAR, CMS, ALICE
Experimental overview of collective flow with identified particles at RHIC and the LHC

Disclaimer

Could not help adding my (in some cases biased) interpretation of results

Panos Christakoglou (Nikhef)
A bit of a history…


A bit of a history…


Random names (faces) from that author list:
A bit of a history…


Random names (faces) from that author list:
The birth of the sQGP paradigm...

The birth of the sQGP paradigm...

…established by looking at the details


Mass ordering at low $p_T$,
Good description by blast-wave parametrisation
...established by looking at the details


Mass ordering at low $p_T$
Good description by blast-wave parametrisation
Agreement with (ideal) hydrodynamical calculations


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Mass ordering at low $p_T$
Good description by blast-wave parametrisation
Agreement with (ideal) hydrodynamical calculations
Apparent NCQ scaling at intermediate $p_T$
**The “perfect liquid” at RHIC**

**Early Universe was a liquid**

Quark-gluon blob surprises particle physicists.

Mark Popkow

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.

Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent 5 years searching for the quark-gluon plasma that is thought to have filled our Universe in the first micro-seconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Quarks and gluons have formed a unexpected liquid. Click here to see animation. © RHIC/BNL

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**Brookhaven National Laboratory**

**RHIC Scientists Serve Up “Perfect” Liquid**

New state of matter more remarkable than predicted -- raising many new questions

Monday, April 18, 2005

TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a liquid.
The “perfect liquid” at RHIC and LHC

Quark-gluon blob surprises particle physicists.

Mark Poplov

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment. Scientists at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory on Long Island, New York, have spent five years searching for the quark-gluon plasma that is thought to have filled our Universe in the first microseconds of its existence. Most of them are now convinced they have found it. But, strangely, it seems to be a liquid rather than the expected hot gas.

Quarks and gluons have formed a unexpected liquid. Click here to see animation. © RHIC/BNL

ALICE
STAR
PHOBOS
PHENIX
NA49
CERES
E877
EOS
E895
FOPI
The sQGP paradigm

- Kinetic freeze-out
- Chemical freeze-out
- Hadron gas
- QGP
- QCD phase transition
- Thermalization
- Parton cascade

$t$, $\tau_f$, $\tau_0$, $z$
Looking at the details: anisotropic flow with identified particles

Important to understand the whole dynamical evolution of the system:
- Initial state
- Viscous hydrodynamical evolution
- Highly dissipative hadronic rescattering phase
The three momentum scales: low $p_T$ ($p_T < 3$ GeV/c)

Mass ordering observed at low $p_T$ at RHIC energies

- expected by hydrodynamic calculations


New calculations expect the mass ordering to be violated
Low $p_T$ ($p_T < 3$ GeV/c): mass ordering $\rightarrow$ elliptic/radial flow interplay
The special role of the $\phi$-meson

At low $p_T$ ($p_T < 3$ GeV/c): mass ordering $\rightarrow$ elliptic/radial flow interplay

First bins could hint to a different ordering? Still inconclusive…
Mass ordering preserved at RHIC?

Mass ordering violation @ RHIC

Mass ordering violation @ RHIC


Probably also for cascades!!!
FIG. 9: (Color online) Transverse momentum dependence of the elliptic flow parameters for pions (dotted blue), protons (dashed green), and $\phi$ mesons (solid red), for Au+Au collisions at $b=7.2$ fm. (a) Before hadronic rescattering. (b) After hadronic rescattering. (c) Ideal hydrodynamics with $T_{th}=100$ MeV. The results for pions and protons are the same as shown in Fig. 5.
Comparison with hydrodynamic calculations

Mass ordering not preserved!!!
Particles with large hadronic x-section are “pushed” to higher $p_T$ (e.g. $p$).
Particles with small hadronic x-section are affected less (e.g. $\varphi$, $\Xi$)
VISH2+1: Centrality 10-20%


- $\pi^\pm$
- $p(\bar{p})$
- $\phi$
- $\Xi^-$ ($\Xi^+$)

$V_2$ vs $p_T$ (GeV/c)

Mass ordering preserved
And there is more…: higher harmonics!
Mass ordering at low $p_T$ observed also for higher harmonics at RHIC
Higher harmonics @ LHC

B. Abelev et al. (ALICE Collaboration), arXiv:1606.06057 [nucl-ex]
Higher harmonics @ LHC (ultra-central events)

B. Abelev et al. (ALICE Collaboration), arXiv:1606.06057 [nucl-ex]

Same features for different $v_n$ (up to $v_5$!) even for ultra-central collisions
The three momentum scales: intermediate $p_T$ ($3 < p_T < 6$ GeV/c)

Number of constituent quark (NCQ) scaling holding with good accuracy at RHIC

- quarks coalesce forming hadrons?
- NCQ scaling was considered as “evidence” of partonic degrees of freedom

Deviations from the universal scaling at RHIC

Deviations from the universal scaling at RHIC


Deviations for $p_T/n_q > 1$ GeV/c depend on centrality
Scaling seems to hold at an approximate level of 10-15%
Good enough???
Scaling properties @ LHC

Intermediate $p_T$ ($3 < p_T < 6 \text{ GeV/c}$): ~grouping based on type (mesons/baryons)

Scaling at the level of no better than ± 20%
NCQ scaling in $p_T/n_q$ (double ratio): evolution with energy

Qualitative similar deviations between LHC and RHIC, but the trend is different for different particle species

The elephant in the room...

ALICE 10-20% Pb-Pb \( s_{NN} = 2.76 \) TeV

Scaling at the level of no better than ± 20%
The special role of the $\phi$-meson

![Graph showing $v_2$ vs $p_T$ for ALICE 40-50% Pb-Pb collisions at $s_{NN} = 2.76$ TeV]
The special role of the $\phi$-meson

Intermediate $p_T$ (3 < $p_T$ < 6 GeV/c) the $\phi$-meson follows the meson band for peripheral events
The special role of the $\phi$-meson

Intermediate $p_T$ (3 < $p_T$ < 6 GeV/c) the $\phi$-meson follows
- the meson band for peripheral events
- the baryon band for central events
The special role of the $\phi$-meson

Mass effect also at the intermediate $p_T$ range!
Challenges the coalescence picture???

Intermediate $p_T$ (3 < $p_T$ < 6 GeV/c) the $\phi$-meson follows
★ the meson band for peripheral events
★ the baryon band for central events
Scaling of higher harmonics @ LHC

B. Abelev et al. (ALICE Collaboration), arXiv:1606.06057 [nucl-ex]
Scaling at the level of 10-20%
AMPT: mass ordering & scaling properties

- A Multi-Phase Transport model
  - String melting:
    - strings are melt into their partons
    - partons interact based on a partonic cross-section
    - coalescence to form hadrons
    - hadronic rescattering phase
  - Default
    - strings combined into hadrons via the Lund string fragmentation model
    - hadronic rescattering phase
- Possibility to probe the effects of the
  - partonic phase
  - coalescence mechanism
  - hadronic rescattering
Mass ordering is mostly created in the hadronic rescattering phase.

Coalescence is responsible of the meson/baryon grouping.
The three momentum scales: high \( p_T > 6 \text{ GeV}/c \)

- Probing the path length dependence
  - particles flying in- (out-of)plane have to travel through less (more) medium
  - expect to see an azimuthal dependence of jets and high \( p_T \) particles
High $p_T$ pions, kaons, protons @ LHC: $v_2$

Significant $v_2$ for all particle species at high $p_T$

- Azimuthal dependence of high-$p_T$ particle yield
- No significant particle species dependence for $p_T > 10$ GeV/c

Theory curve describes data fairly well

Large suppression of high $p_T$ particles

Suppression does not depend on particle species for $p_T > 10$ GeV/c
Searching for the critical point
Similar mass ordering at low $p_T$ as the one reported for higher energies

The $\phi$ seems to deviate from the ordering at lower energies
Similar mass ordering at low $p_T$ as the one reported for higher energies
Spread of $v_2(p_T)$ narrows with energy (not for antiparticles!)
Particle composition, baryon stopping change with energy

Is the difference a “trivial” effect or does it signal the transition to hadronic degrees of freedom?

Models that couple hydro to baryon stopping seem to be getting similar differences with energy

Situation is still quite unclear → need for further input from theorists
BES: Baryon/meson grouping (antiparticles)


Antiparticles

\[ V_2 \]

\[ m_1 - m_0 \text{ (GeV/c}^2\text{)} \]
Τα πάντα ρει… (everything flows)

Ηράκλειτος (Heraclitus) ~535 - 475 BC

ηράκλειτος (Heraclitus) ~535 - 475 BC

Not only in A-A it seems but also for smaller systems!
Not only in A-A it seems but also for smaller systems!

(CMS Collaboration) arXiv:1606.06198 [nucl-ex]

Hράκλειτος (Heraclitus) ~535 - 475 BC

Τα πάντα ρει...(everything flows)
Backup
Not the first time people tried to look at the same details...


The sQGP paradigm

[Diagram showing the sQGP paradigm with labels such as Kinetic freeze-out, Chemical freeze-out, QCD phase transition, Thermalization, Parton cascade, and Hadron gas.]
The sQGP paradigm

- Lattice EoS
- Hydrodynamical evolution ($\eta/s$, $\zeta/s$)
- Initial energy density + fluctuations
- Geometry: Glauber/CGC
- Hadronic rescattering

- sQGP
- Kinetic freeze-out
- Chemical freeze-out
- QCD phase transition
- Thermalization
- Parton cascade
- Hadron gas
- T0
- Beam
- Beam
- t
- $\tau_f$
The sQGP paradigm

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- Parton cascade
- Hadron gas
- QGP
- Hadrons gas
- Photons
- Heavy flavour
- Jets
- Spectra
- HBT

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The sQGP paradigm

Geometry: Glauber/CGC

Initial energy density + fluctuations

Kinetic freeze-out
Chemical freeze-out
QCD phase transition
Parton cascade
Thermalization

Lattice EoS

Hydrodynamical evolution ($\eta/s$, $\zeta/s$)

Hadronic rescattering

sQGP

Photons

Heavy flavour

Anisotropic flow

Jets

Spectra

HBT
Looking at the details
Important to understand the whole dynamical evolution of the system:
- Initial state
- Viscous hydrodynamical evolution
- Highly dissipative hadronic rescattering phase
How does mass ordering develop?

Radial flow pushes particles to higher $p_T$ → depletion at lower $p_T$

★ heavier particles “feel” more the boost → the higher the mass the larger the low $p_T$ depletion

How does mass ordering develop?

Toy model (in-plane)

Toy model (out-of-plane)

$\beta_1 < \beta_2$

$\beta_1 < \beta_2'$
How does mass ordering develop?

Larger “push” in-plane than out-of-plane as a function of mass

- Larger low-$p_T$ depletion in-plane than out-of-plane → lower $v_2$ in a mass dependent way
How does mass ordering develop?

Larger “push” in-plane than out-of-plane as a function of mass

larger low-$p_T$ depletion in-plane than out-of-plane → lower $v_2$ in a mass dependent way

Heavy particles have lower $v_2$ at a fixed $p_T$ than light particles
Systematic deviations for the majority of particle species (with the exception of K)

Proton $v_2$ underestimated (i.e. extra push expected in hydro) but $\Lambda$ $v_2$ overestimated (i.e. less push expected in hydro)

Mass ordering not preserved in VISHNU due to the hadronic cascade

not supported by ALICE data
How about higher harmonics?

Number of constituent quark (NCQ) scaling in $p_T/n_q$

ALICE

Pb-Pb $\varsigma_{NN} = 2.76$ TeV

$|\eta| < 0.8$

and $|y| < 0.5$

Particle species

- $\pi^+$
- $K$
- $p+\bar{p}$
- $\phi$
- $\Lambda + \bar{\Lambda}$
- $\Xi^- + \Xi^+$
- $\Omega + \bar{\Omega}^+$

$V_2[SP,|\eta| > 0.9]/n_q$

$p_T/n_q$ (GeV/c)
Number of constituent quark (NCQ) scaling in $p_T/n_q$

Relevant range: $p_T/n_q > 1$ GeV/c
The special role of the $\phi$-meson

Important test of:

- mass ordering at low $p_T$
- the particle type grouping at intermediate $p_T$
The special role of the $\phi$-meson

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- mass ordering at low $p_T$
- the particle type grouping at intermediate $p_T$


The special role of the $\phi$-meson

Important test of:
★ mass ordering at low $p_T$
★ the particle type grouping at intermediate $p_T$

Mass effect also at the intermediate $p_T$ range!
Challenges the coalescence picture???

At low $p_T$ ($p_T < 3$ GeV/c): mass ordering $\Rightarrow$ elliptic/radial flow interplay
★ First bins could hint to a different ordering? Still inconclusive…

Intermediate $p_T$ ($3 < p_T < 6$ GeV/c) the $\phi$-meson follows
★ the baryon band for central events
★ the meson band for peripheral events
Violation of mass ordering at RHIC

Number of constituent quark (NCQ) scaling in $p_T/n_q$

Scaling only approximate
NCQ scaling in $p_T/n_q$ (double ratio)

ALICE

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$|\eta| < 0.8$

and $|y| < 0.5$

Particle species
- $\pi^\pm$
- $K$
- $p+\bar{p}$
- $\phi$
- $\Lambda+\bar{\Lambda}$
- $\Xi^-+\bar{\Xi}^+$
- $\Omega^++\bar{\Omega}^+$

$p_T/n_q$ (GeV/c)
NCQ scaling in $p_T/n_q$ (double ratio)

Scaling at the level of no better than ± 20%
NCQ scaling in \((m_T - m_0)/n_q\)

ALICE
Pb-Pb \(\sqrt{s_{NN}} = 2.76\) TeV
\(|\eta| < 0.8\
and \(|y| < 0.5\)

Particle species
- \(\pi^+\)
- \(K\)
- \(p + \bar{p}\)
- \(\phi\)
- \(\Lambda + \bar{\Lambda}\)
- \(\Xi^+ + \Xi^-\)
- \(\Omega + \bar{\Omega}^+\)
NCQ scaling in \((m_T - m_0)/n_q\)

Introduced to extend the scaling to lower \(p_T\)
NCQ scaling in $(m_T - m_0)/n_q$ (double ratio)

ALICE

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV

$|n| < 0.8$

and $|y| < 0.5$

Particle species

- $\pi^\pm$
- $K$
- $p+\bar{p}$
- $\phi$
- $\Lambda+\bar{\Lambda}$
- $\Xi^-+\Xi^+$
- $\Omega^-+\Omega^+$

$(v_2/n_q)/(v_2/FitP)$

$(m_T - m_0)/n_q$ (GeV/$c^2$)
NCQ scaling in \((m_T - m_0)/n_q\) (double ratio)

For \((m_T - m_0)/n_q < 0.6 - 0.8 \text{ GeV}/c^2\): scaling is broken at the LHC

For \((m_T - m_0)/n_q > 0.6 - 0.8 \text{ GeV}/c^2\): scaling is only approximate at the level of ± 20%
Scaling of higher harmonics @ RHIC

AMPT string melting describes the main features observed in data qualitatively.

AMPT string melting fails to describe data quantitatively.

Radial flow reduced in AMPT by 25% compared with data.
Spectra: How good is VISHNU doing?

Pb+Pb 2.76 A TeV (LHC)

$\frac{dN}{dy(\sqrt{s})} (GeV^{-2})$

$\frac{dN}{d\phi (\sqrt{s})} (GeV^{-2})$

$\frac{dN}{d\eta (\sqrt{s})} (GeV^{-2})$

$\frac{dN}{d\phi (\sqrt{s})} (GeV^{-2})$

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$\frac{dN}{d\phi (\sqrt{s})} (GeV^{-2})$
VISH2+1: comparison to spectra

Mass ordering is not preserved!!!
Importance of hadronic rescattering phase: VISHNU vs VISH2+1

Couples VISH2+1 to UrQMD

$\eta/s = 0.16$

$\tau_0 = 0.9 \text{ fm/c}$

VISHNU

VISH2+1


Mass ordering is not preserved

Not a clear trend: \( \pi, K \) similar for both centralities, \( \phi \) similar for central events but different for peripheral, some baryons (e.g. p, \( \Lambda \)) “pushed” to higher \( p_T \), while others (e.g. \( \Xi \)) to lower \( p_T \)
Mass ordering preserved
NCQ scaling in \((m_T - m_0)/n_q\) (double ratio)

For \(\frac{(m_T - m_0)}{n_q} < 0.6 - 0.8 \text{ GeV}/c^2\): scaling is broken at the LHC

For \(\frac{(m_T - m_0)}{n_q} > 0.6 - 0.8 \text{ GeV}/c^2\): scaling is only approximate at the level of ± 20%
Scaling properties at the LHC

Scaling at the level of no better than ± 20%
Qualitative similar deviations between LHC and RHIC, but the trend is different for different particle species.
NCQ scaling in $p_T/n_q$ (double ratio): evolution with energy

Qualitative similar deviations between LHC and RHIC, but the trend is different for different particle species

Universal scaling of $v_2$ observed at RHIC?

Experimental observations indicated that the scaling works fairly well at RHIC. Supported the idea that flow develops mainly at the partonic stage.

Deviations from the universal scaling at RHIC


Deviations for $KE_{\pi}/n_\pi > 0.8 \text{ GeV}/c^2$ depend on centrality
Deviations from the universal scaling at RHIC


Similar deviations observed by STAR?
Scaling holds at the same level (±10-15%) as for higher energies for particles and antiparticles separately.

The Quark-Gluon Plasma (QGP): a state of matter where the quarks and gluons are the relevant degrees of freedom.

We believe that the universe after expanding and cooling down went through this phase few μs after the Big-Bang.

Studying the strong phase transition → study primordial matter.
QCD: Phase transition beyond a critical temperature (~170 MeV) and energy density (~0.5 GeV/fm\(^3\)) → quarks and gluons are free → Quark Gluon Plasma (QGP)

The properties of the QGP and the QCD Phase transition are poorly known from first principles

\[ T_{(QGP\text{-transition})} \approx 170 \text{ MeV} \rightarrow 10^{12} \text{ degrees} \]

\[ T_{(\text{Sun’s core})} \approx 10^7 \text{ degrees} \]

\[ T_{(QGP\text{-transition})} = 10^5 \times T_{(\text{Sun’s core})} \]
Colliding Au-ions at

- $\sqrt{s_{NN}} = 130$ and 200 GeV (RHIC “high energies”) $\rightarrow$ mapping the crossover region for the first time
- $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39,$ and 62.4 GeV $\rightarrow$ searching for the critical point in the phase diagram (BES: Beam Energy Scan)
Little Bangs studied at RHIC and LHC

Colliding Pb-ions at $\sqrt{s_{NN}} = 2.76$ TeV ➞ quantifying the QGP properties at $\mu_B \sim 0$

Colliding Au-ions at

- $\sqrt{s_{NN}} = 130$ and 200 GeV (RHIC “high energies”) ➞ mapping the crossover region for the first time
- $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39,$ and 62.4 GeV ➞ searching for the critical point in the phase diagram (BES: Beam Energy Scan)
Elliptic flow

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$
Elliptic flow

\[ \epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]
Superposition of independent pp collisions

\[ \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]
Elliptic flow

Superposition of independent pp collisions

Momenta pointing at random directions

\[ \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]
Development as a bulk system

Elliptic flow

high density and pressure at the center of the fireball

\[ \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]
Development as a bulk system

Asymmetric pressure gradients (larger in-plane than out-of-plane) push bulk out → flow

high density and pressure at the center of the fireball

\[\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}\]
Development as a bulk system

Asymmetric pressure gradients (larger in-plane than out-of-plane) push bulk out → flow

More and faster particles in-plane than out-of-plane

Elliptic flow

\[ \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \]

high density and pressure at the center of the fireball
Elliptic flow

Superposition of independent pp collisions

\[
\phi - \Psi_2 \text{ (rad)}
\]

\[N\]

0 \[\pi/4\] \[\pi/2\] \[3\pi/4\] \[\pi\]
Elliptic flow

Superposition of independent pp collisions

\[ \phi - \Psi_2 \text{ (rad)} \]
Elliptic flow

Superposition of independent pp collisions

Development as a bulk system
Elliptic flow

Superposition of independent pp collisions

Development as a bulk system

\[ \nu_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle} \quad \nu_2(p_T, \eta) = \langle \cos[2(\phi - \Psi_2)] \rangle \]
Probing the properties of the QGP

The Phases of QCD

- Early Universe
- LHC Experiments
- RHIC Experiments
- RHIC Energy Scan
- Critical Point
- Hadron Gas
- Quark-Gluon Plasma
- Future FAIR Experiments
- 1st order phase transition
- Color Superconductor
- Nuclear Matter
- Neutron Stars
- Baryon Chemical Potential
Studying the properties of the QGP


EVIDENCE FOR A DENSE LIQUID

Two phenomena in particular point to the quark-gluon medium being a dense liquid state of matter: jet quenching and elliptic flow. Jet quenching implies the quarks and gluons are closely packed, and elliptic flow would not occur if the medium were a gas.

JET QUENCHING

In a collision of protons, hard scattering of two quarks produces back-to-back jets of particles.

In the dense quark-gluon medium, the jets are quenched, like bullets fired into water, and on average only single jets emerge.

ELLIPITIC FLOW

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium.

The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (arrows).