Flow and soft phenomena in heavy-ion collisions

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Latest results at Quark Matter 2014: http://qm2014.gsi.de
Emergent phenomena in QCD

Soft QCD is the least understood part of standard model
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“A” → “More is different” – P. W. Anderson

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Emergent phenomena in QCD

Soft QCD is the least understood part of standard model

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In heavy-ion collisions: search for and study emergent phenomena in many-body QCD system
Discovery of a “nearly perfect” liquid at RHIC

elliptic flow:

\[ \frac{dN}{d\Delta \phi} \sim 1 + 2v_2 \cos[2(\phi - \Psi_{EP})] \]
Discovery of a “nearly perfect” liquid at RHIC

Strong collectivity of final-state particles discovered at RHIC

Behaving as a strongly coupled liquid with minimal frictional resistance ($\eta/s$)
QGP and flow at the LHC

![Graph showing the increase in total transverse energy (E_T) with 
\( \sqrt{s_{NN}} \) from RHIC to LHC.]

2 TeV per unit \( \eta \)

Total transverse energy (E_T)

- **FOPI, 0-1% AuAu**
- **E802, 0-5% AuAu**
- **NA49, 0-7% PbPb**
- **WA98, 0-5% PbPb**
- **PHENIX, 0-5% AuAu**
- **CMS, 0-5% PbPb**

3-fold increase from RHIC to LHC

**A hotter QGP!**
QGP and flow at the LHC

Total transverse energy ($E_T$)

2 TeV per unit $\eta$

3-fold increase from RHIC to LHC

A hotter QGP!

Strong collective flow persists at the LHC

FOPI, 0-1% AuAu
E802, 0-5% AuAu
NA49, 0-7% PbPb
WA98, 0-5% PbPb
PHENIX, 0-5% AuAu
CMS, 0-5% PbPb

RHIC parametrization

$0.46 \sqrt{s_{NN}} \gtrsim 8.7$ GeV

PRL 109 (2012) 152303

arXiv:1405.3936
Elliptic flow at the LHC

\[ v_2 \text{ vs } p_T \]

**PRC 87(2013) 014902**

- CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV
- STAR AuAu $\sqrt{s_{NN}} = 200$ GeV

CMS fit

**Similar flow at RHIC and the LHC**
Elliptic flow at the LHC

Similar flow at RHIC and the LHC
Flow with identified particles

- Mass ordering at low $p_T$: Smaller $v_2$ for heavier particles
- $v_2$(baryon) > $v_2$ (meson) at higher $p_T$

ALICE PbPb 2.76 TeV
10-20% centrality

$\pi$, $K$, $p$, $\phi$, $\Lambda$, $\Xi$, $\Omega$
Flow with identified particles

- Mass ordering at low $p_T$: Smaller $v_2$ for heavier particles
- $v_2$(baryon) $> v_2$ (meson) at higher $p_T$

In hydro, radial flow boosts heavier particles to higher $p_T$

$\Delta p_T \sim m \beta_T$
Flow, two-particle correlations, ridge …

\[ \sim 1 + 2(v_2^2) \cos(2\Delta \phi) \]

CMS PbPb 2.76 TeV
35-40%

\[ |\Delta \eta| > 2 \]

\[ \Psi_{EP} \]

\[ \Delta \phi \]

\[ 1 \]

\[ 2 \]

\[ N_{\text{pair}} \]

\[ \frac{1}{N_{\text{pair}}} \frac{dN}{d\Delta \phi} \]

arXiv:1201.3158
Flow, two-particle correlations, ridge ...

Elliptic flow is long-range in pseudorapidity ($\eta$)

$\Delta\eta$-$\Delta\phi$ correlation:

CMS PbPb 2.76 TeV

No near-side ridge in MB pp

(b) MinBias, 1.0 GeV/c < $p_T$ < 3.0 GeV/c

Too small object to thermalize

~ $1 + 2(v_2^2)$ cos(2$\Delta\phi$)

arXiv:1201.3158
Flow, two-particle correlations, ridge ...

Elliptic flow is long-range in pseudorapidity (\(\eta\))

\(\Delta\eta-\Delta\phi\) correlation:

CMS PbPb 2.76 TeV

35-40%

central PbPb events

CMS Preliminary
PbPb \(\sqrt{s_{NN}} = 2.76\) TeV

arXiv:1201.3158

\(\sim 1 + 2(v_2^2)^2 \cos(2\Delta\phi)\)
Initial “QGP shape” includes higher multipole components

\[ \bar{\varepsilon}_2 \bar{\varepsilon}_3 \bar{\varepsilon}_4 = \varepsilon_2 \cos 2 \Delta \phi + \varepsilon_3 \cos 3 \Delta \phi + \varepsilon_4 \cos 4 \Delta \phi + \varepsilon_5 \cos 5 \Delta \phi + \ldots \]
Higher-order deformation of initial state

Initial "QGP shape" includes higher multipole components

\[ \epsilon_2 \cos 2\Delta \phi + \epsilon_3 \cos 3\Delta \phi + \epsilon_4 \cos 4\Delta \phi + \epsilon_5 \cos 5\Delta \phi + \ldots \]

ALICE
Pb-Pb 2.76 TeV, 0-2% central

\[ \chi^2/\text{ndf} = 33.3 / 35 \]

PLB 708 (2012) 249

Wei Li (Rice) LHCP 2014
Higher-order deformation of initial state

Initial "QGP shape" includes higher multipole components

\[ \varepsilon_2 \cos 2\Delta\phi + \varepsilon_3 \cos 3\Delta\phi + \varepsilon_4 \cos 4\Delta\phi + \varepsilon_5 \cos 5\Delta\phi + \ldots \]

Hydro faithfully transposes the initial shape into final-state particle azimuthal distributions
Flow in ultra-central PbPb collisions

Initial-state geometry dominated by density perturbations

PbPb collisions with $b \sim 0$, almost symmetric on average
Flow in ultra-central PbPb collisions

Initial-state geometry dominated by density perturbations

Top 0.2% central

PbPb collisions with b ~ 0, almost symmetric on average

Better agreement by including nucleon-nucleon correlations and bulk viscosity

CMS
PbPb $\sqrt{s_{NN}} = 2.76$ TeV
0.3<\(p_T\)<3 GeV/c

VISH2+1 Hydro
- Glauber, $\eta/s=0.08$
- MC-KLN, $\eta/s=0.2$

Wei Li (Rice)

LHCP 2014
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Better agreement by including nucleon-nucleon correlations and bulk viscosity

$\eta/s$ indeed very small: $\sim 0.08 - 0.2$
Flow in ultra-central PbPb collisions

Initial-state geometry dominated by density perturbations

Top 0.2% central

JHEP 02 (2014) 088

CMS
PbPb $\sqrt{s_{\text{NN}}}$ = 2.76 TeV
0.3<p_T<3 GeV/c

VISH2+1 Hydro
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Better agreement by including nucleon-nucleon correlations and bulk viscosity

Mapping out propagation of initial perturbations as system evolves
Event-by-event flow fluctuations

Initial-state geometry fluctuates on an \textit{event-by-event} basis
Event-by-event flow fluctuations

Initial-state geometry fluctuates on an **event-by-event** basis

So does the response of final-state flow effect ($v_n, \Phi_n$)?

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos n (\phi - \Phi_n)
\]
Event-by-event flow fluctuations

Full event-by-event $v_2$ distribution (unfolded for finite resolution)

- ATLAS Pb+Pb
- $p_T > 0.5$ GeV, $|\eta| < 2.5$
- $|s_{NN}| = 2.76$ TeV
- $L_{int} = 7 \mu b^{-1}$

JHEP 11 (2013) 183
Event-by-event flow fluctuations

Full event-by-event $v_2$ distribution (unfolded for finite resolution)

Successfully described by hydrodynamics, again
More on flow fluctuations …

Correlation between different Event plane angle ($\Phi_2$ and $\Phi_4$)

Anti-correlations between $v_2$ and $v_3$, expected from initial geometry

arXiv:1403.0489
“Nearly perfect liquid” paradigm of heavy-ion collisions firmly established at RHIC and the LHC

A phase of precision measurement, aiming to quantify the properties of QGP in detail
Breaking news In 2010:

*A near-side ridge in pp at the LHC!*

- pp 7 TeV, N>=110
- 1<p_T<3 GeV/c
- 0-0.0007% central

JHEP 09 (2010) 091
A big strike in 2010 ...

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Mini-QGP fluid (r ~ 1 fm) in pp?

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Mini-QGP fluid ($r \sim 1$ fm) in pp?

Beginning of a second “discovery” phase

JHEP 09 (2010) 091
The ridge is everywhere: pPb at the LHC

pp 7 TeV, N>=110

CMS Preliminary
PbPb \sqrt{s_{NN}} = 2.76 TeV

35-40%
The ridge is everywhere: pPb at the LHC

PP 7 TeV, N>=110

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{trig}^{mm} \geq 110$

CMS Preliminary

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

PRL 110 (2013) 182302

ATLAS p+Pb $\sqrt{s_{NN}}$=5.02 TeV, $\int L = 1 \mu b^{-1}$

Pb 35-40%

PLB 718 (2013) 795
The ridge is everywhere: pPb at the LHC

pp 7 TeV, N>=110

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{trig}^{miss} \geq 110$

$1 < p_T < 3$ GeV/c

PLB 718 (2013) 795

Ridge in dAu at RHIC!

arXiv:1404.7461

CMS Preliminary

Ridge in dAu at RHIC!
Flow ($v_n$) in pPb

Fourier again ...

**ATLAS** Preliminary

$\sqrt{s_{NN}} = 5.02$ TeV

$L_{int} = 28$ nb$^{-1}$

$p+Pb$

$220 \leq N_{ch}^{\text{rec}} < 260$

$1 < p_T^b < 3$ GeV, $|\Delta \eta| > 2$

- $n=2$
- $n=3$
- $n=4$
- $n=5$

**CMS**, $220 \leq N_{\text{trk}}^{\text{off}} < 260$

- $v_2$, $N_{\text{trk}}^{\text{off}} < 20$ sub.
- $v_3$, $N_{\text{trk}}^{\text{off}} < 20$ sub.

ATLAS-CONF-2014-021

LHCP 2014
Flow ($v_n$) in pPb

Fourier again ...

ATLAS Preliminary

220 ≤ $N_{ch}^{MC}$ < 260
1 < $p_T^b$ < 3 GeV, $|\Delta \eta| > 2$

n=2
n=3
n=4
n=5

CMS, 220 ≤ $N_{trk}^{off}$ < 260

$V_2$, $N_{trk}^{off}$ < 20 sub.
$V_3$, $N_{trk}^{off}$ < 20 sub.

Intriguing similarity between pPb and PbPb!
Triangular flow nearly identical in pPb and PbPb!

Triangularity entirely from fluctuations, maybe system size does not matter?

Teaney, arXiv:1312.6770
Triangular flow nearly identical in pPb and PbPb!

But, hydro. failed to describe the data

\[ \varepsilon_3 \text{ driven by proton, which is too small since proton is spherical in the model} \]

Tianey, arXiv:1312.6770
Flow ($v_n$) in pPb

Triangular flow nearly identical in pPb and PbPb!

But, hydro. failed to describe the data

ε₃ driven by proton, which is too small since proton is spherical in the model

Stringy proton from quantum fluctuations caught by a nucleus?

Teaney, arXiv:1312.6770

PrD 89, 025019 (2014)
Mass splitting of $v_2$ in pPb:

- Smaller $v_2$ for heavier particles at low $p_T$
- Consistent with hydro.
PID $v_n$ in pPb

Strange hadrons: $K^0_S$ and $\Lambda$

- Smaller $v_2$ for heavier particles at low $p_T$
- Consistent with hydro.

Clear crossing at $p_T \sim 2$ GeV
Mass splitting of $v_2$ in pPb:
- Smaller $v_2$ for heavier particles at low $p_T$
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Clear crossing at $p_T \sim 2$ GeV

No mass dependence of Jet correlations at low $N_{\text{trk}}$
Larger mass splitting in pPb than in PbPb at similar multiplicity

⇒ Stronger radial flow for smaller and denser system?
True collectivity in pPb?

The key question:

Does the ridge involve only two particles or more?
True collectivity in pPb?

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Or namely, is it a collective effect as hydro. describes?
True collectivity in pPb?

The key question:

**Does the ridge involve only two particles or more?**

Or namely, *is it a collective effect as hydro. describes?*

Multi-particle (>2) correlations:

\[
\langle \cos 2(\phi_1 - \phi_2) \rangle \sim (v_2)^2
\]

\[
\langle \cos 2(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle \sim (v_2)^4
\]

\[
\langle \cos 2(\phi_1 + \phi_2 + \phi_3 - \phi_4 - \phi_5 - \phi_6) \rangle \sim (v_2)^6
\]

In hydrodynamics:

\[v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}\]
True collectivity in pPb?

\[ v_{2\{2\}} > v_{2\{4\}} \]
(event-by-event fluctuations)

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**Left Panel:**
- PbPb \( \sqrt{s_{NN}} = 2.76 \) TeV
- \( 0.3 < p_T < 3.0 \) GeV/c; \( |\eta| < 2.4 \)

**Right Panel:**
- pPb \( \sqrt{s_{NN}} = 5.02 \) TeV
- \( 0.3 < p_T < 3.0 \) GeV/c; \( |\eta| < 2.4 \)

\( v_2 \) vs. \( N_{\text{offline}}^\text{trk} \) (event multiplicity)
True collectivity in pPb?

\[ v_2\{2\} > v_2\{4\} \approx v_2\{6\} \]

(event-by-event fluctuations)
True collectivity in pPb?

$v_2^2 > v_2^4 \approx v_2^6 \approx v_2^8$

(event-by-event fluctuations)
True collectivity in pPb?

$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\text{LYZ, } \infty\}$

(event-by-event fluctuations)

Direct evidence of strong collectivity in pPb!
Toward a unified picture from pp, pA to AA

![Graph showing v3 vs. N_{tracks} (multiplicity) for CMS, pA, and AA with various data points and curves.](image)

- CMS: 0.3 < p_T < 3 GeV/c
- pA: v_3 (N_{tracks} < 2.4)
- AA: v_3 (N_{tracks} > 2.4)

Legend:
- Red circles: PbPb $\sqrt{s_{NN}} = 5.02$ TeV, $v_3$ (2, |$$\eta$$|>2)
- Blue squares: PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $v_3$ (2, |$$\eta$$|>2)
- Blue squares: PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $v_3$ (EP, <$$p_T$$> = 1.6)
- Black line: Hydro PbPb, IP-Glasma, $p_T$ > 0.2 GeV/c
Toward a unified picture from pp, pA to AA

Hydrodynamics paradigm in AA
Toward a unified picture from pp, pA to AA

Discovery of *collective* “flow” phenomena in pA

Hydrodynamics paradigm in AA
Toward a unified picture from pp, pA to AA

Discovery of *collective* “flow” phenomena in pA

Other interpretations:
- Quantum entanglement of gluons: PRD 87 (2013) 094034
Toward a unified picture from pp, pA to AA

Discovery of collective “flow” phenomena in pA

Other interpretations:
- Quantum entanglement of gluons: PRD 87 (2013) 094034

Hydrodynamics paradigm in AA

- Is it also collectivity in pp?
- Jet quenching in pp and pA?
- If indeed everything flows, what’s the mechanism of thermalization?
Toward a unified picture from pp, pA to AA

Discovery of collective “flow” phenomena in pA

Other interpretations:
- Quantum entanglement of gluons: PRD 87 (2013) 094034

- Is it also collectivity in pp?
- Jet quenching in pp and pA?
- If indeed everything flows, what’s the mechanism of thermalization?

Stay tuned for more excitements!
Backup