Azimuthal flow and correlations in HI

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Heavy ion collision overview

Physics

Initial conditions and Collision geometry
- Shape
- Size
- Fluctuations

Quark-gluon plasma
- Transport properties
  - Shear and bulk viscosities
- Speed of sound

Initial state
QGP phase
Hadronization
Freeze-out
Final detected particles

Time: 0 fm/c
< 1 fm/c
~10 fm/c
~10^{15} fm/c

Transverse momentum
Azimuthal flow and correlations at LHC – recent results

**Observables**

- **Azimuthal flow**: Fourier coefficients $v_n$
  - $v_n$ extended to forward region in pseudorapidity (ALICE and LHCb)
  - Ridge yield in low multiplicity (ALICE)
  - $v_2$ at high $p_T$, with/without jets, or inside jet cone (ATLAS and CMS)
  - Flow decorrelations (ALICE and ATLAS)

- **Bose-Einstein correlations / Femtoscopic correlations**
  - Correlation radius in pPb (LHCb)
  - Correlation radius in pp with event shape selection (ALICE)

- **Mean transverse momentum**
  - $<p_T>$ fluctuations (ALICE and ATLAS)
  - $<p_T>$ in ultra-central collisions (CMS)

**Physics**

- **Initial conditions and Collision geometry**
  - Shape
  - Size
  - Fluctuations

- **Quark-gluon plasma**
  - Transport properties
    - Shear and bulk viscosities
  - Speed of sound
$v_n$ extended to forward region (ALICE)

- The decrease in forward is described by hydrodynamics
- AMPT reproduces the asymmetry in p-going vs Pb-going
$v_n$ extended to forward region (ALICE and LHCb)

- The decrease in forward is described by hydrodynamics
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Ridge yield in low multiplicity (ALICE)

- Ridge yield extended to low multiplicity region
- Models cannot describe the yield at low multiplicity: mechanisms not understood
Identified particle $v_2$ in low multiplicity (ALICE)

- Baryon-meson grouping and splitting of $v_2$: described by Hydro+Coal+Frag, not transport

N_{ch}>50

\[ \text{Hydro-Coal+Frag} \]

\[ \text{AMPT (String-melting)} \]

Identified particle $v_2$ in low multiplicity (ALICE)

- **Baryon-meson grouping and splitting of $v_2$**: described by Hydro+Coal+Frag, not transport

- **No evidence of baryon-meson grouping and splitting of $v_2$** at intermediate $p_T$ in low multiplicity

**New**

**$25 < N_{ch} < 50$**

**p–Pb: 15 < $N_{ch}$ < 25**

**pp: 15 < $N_{ch}$ < 25**
Ultra long-range $v_2$ in low multiplicity (ALICE)

- **Baryon-meson grouping and splitting of $v_2$:** Described by Hydro+Coal+Frag, not transport.
- **No evidence of baryon-meson grouping and splitting of $v_2$ at intermediate $p_T$ in low multiplicity**.

- **Ultra long-range correlations:** Both hydro and transport models are failing to describe data.

- **No evidence of baryon-meson grouping and splitting of $v_2$ at intermediate $p_T$ in low multiplicity.**
$v_2$ in events WithJets/NoJets (ATLAS)

- $v_2$ is not affected by jets
- Jet constituents have zero $v_2$
$v_2$ in events WithJets/NoJets, at high $p_T$ (ATLAS and CMS)

- $v_2$ is not affected by jets
- Jet constituents have zero $v_2$
- High $p_T$ $v_2$ nonflow removal needed with 3 or 4 subevents
- Same $v_2$ in pPb and PbPb at $p_T > 8$ GeV
$v_2$ inside jet cone (CMS)

- Take jet direction as the z-axis and redefine kinematics
- Clear near side peak at long range observed in high $N_{ch}$
- $v_2$ shows a distinct increase for $N_{ch} \geq 80$, not reproduced in models

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Flow decorrelations (ALICE)

- Models can only reproduce trends for some of the decorrelation results

\[ r_n = \frac{V_{n\alpha}(p_T^1, p_T^j)}{\sqrt{V_{n\alpha}(p_T^1, p_T^1) V_{n\alpha}(p_T^j, p_T^j)}} \]

Flow angle fluctuations:

\[ A_n^f = \frac{1}{2} \left( \sqrt{\cos^2 n(\Psi_n(p_T) - \Psi_n)} + \cos n(\Psi_n(p_T) - \Psi_n) \right) \]
Flow decorrelations (ALICE and ATLAS)

• Models can only reproduce trends for some of the decorrelation results
Bose-Einstein correlations (ALICE)

\[ S_T = \frac{2 \min(\lambda_1, \lambda_2)}{\lambda_1 + \lambda_2} \]

\( \lambda_1 \) and \( \lambda_2 \) are the eigenvalues of the matrix of \( p_T \)

\[
S_T = \frac{1}{\sum_i p_T^i} \sum_i \left( \frac{(p_T^i)^2}{p_T^i} \begin{pmatrix} p_X^i & p_Y^i \\ p_X^i & (p_Y^i)^2 \end{pmatrix} \right)
\]

- \( S_T \to 0 \): jetty limit (hard events)
- \( S_T \to 1 \): spherical limit (soft events)

- Spherical events have larger emitting source
- \( R_{inv} \) decreases as \( m_T \) increases
Bose-Einstein correlations (ALICE and LHCb)

\[ S_T = \frac{2 \min(\lambda_1, \lambda_2)}{\lambda_1 + \lambda_2} \]

\( \lambda_1 \) and \( \lambda_2 \) are the eigenvalues of the matrix of \( p_T \)

\[ S_T = \frac{1}{\sum_i p_T^i} \sum_i 1 \left( \begin{array}{cc} (p_X^i)^2 & p_X^i p_Y^i \\ p_X^i p_Y^i & (p_Y^i)^2 \end{array} \right) \]

- \( S_T \rightarrow 0 \): jetty limit (hard events)
- \( S_T \rightarrow 1 \): spherical limit (soft events)

- Spherical events have larger emitting source
- \( R_{inv} \) decreases as \( m_T \) increases
- Scaling of \( R \) with cube root of \( N_{VELO} \)
  - Agree with hydrodynamic predictions

\[ \frac{R}{(N_{VELO})^{1/3}} \]

**Fit:** \( R \sim (N_{VELO})^{1/3} \)

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Positive skewness and Kurtosis, both decrease as $dN_{ch}/d\eta$ increases
• Positive skewness and Kurtosis, both decrease as dN_{ch}/d\eta increases
• Hydrodynamic models reproduce the results in central and mid-central collisions
\( \langle p_T \rangle \) in ultra-central collisions and speed of sound (CMS)

- Sound modes arising from longitudinal compression wave propagating in the fluid medium: \( c_s \)
  - Directly constrains the equation of state
- A steep rise of \( \langle p_T \rangle \) is observed in ultra-central
  - Agree with hydrodynamic model predictions
- \( c_s^2 = 0.241 \pm 0.002 \text{ (stat)} \pm 0.016 \text{ (syst)} \)
- First time determination of \( c_s \) with high precision

Extracting \( c_s^2 \) with:

\[
\frac{\langle p_T \rangle}{\langle p_T \rangle^0} \sim \left( \frac{N_{ch}}{N_{ch}^0} \right)^{c_s^2}
\]

\( N_{ch}^0 \) and \( \langle p_T \rangle^0 \) from 0-5% centrality
Extracting speed of sound is more complicated (ALICE)

**Extraction of $c_s^2$ depends on the centrality determination**
- Forward vs. midrapidity
- ITS tracklets vs full tracks
- $E_T$ vs $N_{ch}$

**Decreased $c_s^2$ using forward centrality determination**
**Increased $c_s^2$ using $E_T$**
Extracting speed of sound is more complicated (ALICE)

Midrapidity: $N_{ch}$ (II) and $N_{tracklet}$ (VI) and forward $N_{ch}$ (IX)

$\langle p_T \rangle$ vs. $\frac{dN_{ch}}{d\eta} / \langle N_{ch} \rangle$ (0.5%)

- ALICE Preliminary
- Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
- Centrality selectors
  - II, $c_2^2 = 0.178^{+0.008}_{-0.007}$ (syst)
  - VII, $c_2^2 = 0.143^{+0.007}_{-0.006}$ (stat)
  - VI, $c_2^2 = 0.113^{+0.003}_{-0.003}$ (stat)

$E_T$: No subevent (V) and subevent (IV)

$\langle p_T \rangle$ vs. $\frac{dN_{ch}}{d\eta} / \langle N_{ch} \rangle$ (0.5%)

- Centrality selectors
  - I, $c_2^2 = 0.137^{+0.002}_{-0.001}$ (syst)
  - III, $c_2^2 = 0.438^{+0.016}_{-0.011}$ (syst)
  - V, $c_2^2 = 0.170^{+0.007}_{-0.001}$ (stat)
  - IV, $c_2^2 = 0.306^{+0.006}_{-0.006}$ (stat)

Speed of sound vs. $\eta$ gap; Robust?

Lattice QCD at $T = 222$ MeV

Observable | Label | Centrality estimation | $\langle p_T \rangle$ and $\langle dN_{ch}/d\eta \rangle$ | $\eta$ gap
---|---|---|---|---
$N_{ch}$ in TPC | I | $|\eta| \leq 0.8$ | $|\eta| \leq 0.8$ | 0
II | $0.5 \leq |\eta| \leq 0.8$ | $|\eta| \leq 0.3$ | 0.3
III | $|\eta| \leq 0.8$ | $|\eta| \leq 0.3$ | 0.3
IV | $0.5 \leq |\eta| \leq 0.8$ | $|\eta| \leq 0.3$ | 0.3
$E_T$ in TPC | V | $|\eta| \leq 0.8$ | $|\eta| \leq 0.8$ | 0
VI | $0.5 \leq |\eta| \leq 0.8$ | $|\eta| \leq 0.3$ | 0.3
VII | $0.3 \leq |\eta| \leq 0.6$ | $|\eta| \leq 0.3$ | 0
VIII | $0.7 \leq |\eta| \leq 1$ | $|\eta| \leq 0.3$ | 0.4
$N_{ch}$ in V0 | IX | $-3.7 < \eta < -1.7 + 28 < \eta < 5.1$ | $|\eta| \leq 0.8$ | 1.7
$\Lambda$ polarization in pPb (CMS)

The results might indicate complex vorticity structures in pPb collisions

Flow $\rightarrow$ Vorticity $\rightarrow$ Spin-orbit coupling $\rightarrow$ polarization
Summary

• Rich results from flow and correlations at LHC
  – Flow extended to forward region, including in pPb
  – Ridge yield and PID $v_2$ extracted at low multiplicity in pp and pPb
  – Relation between flow and jets studied in detail in small systems
  – New flow decorrelations for understanding longitudinal dynamics
  – Bose-Einstein correlations with event shape engineering
  – Power hiding behind $<p_T>$ is revealed: speed of sound in QGP
  – $\Lambda$ polarization observed in pPb
• Work on Run3 data is ongoing

Full list of results at LHC:

ALICE    ATLAS    CMS    LHCb