Recent measurements of azimuthal anisotropy $v_n$ in heavy ion collisions

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Outline

- Azimuthal anisotropy in $p(d)+A$ collisions
- HBT measurements in $p(d)+A$ collisions
- Event shape control study in $A+A$ collisions
Initial Fluctuations

Simplified Distribution
- Initial spatial anisotropy ⇒ Momentum anisotropy
- Only second-order event-plane

Ev-by-Ev Fluctuating Distribution
- Higher-order event-planes
\[ dN/d\Phi \propto 1 + \sum 2v_n \cos n(\Phi - \Psi_n) \]

\[ \varepsilon_n^{part} = \sqrt{\frac{\langle r^2 \cos n\phi_{part} \rangle^2 + \langle r^2 \sin n\phi_{part} \rangle^2}{\langle r^2 \rangle}}, \]
\[ \Psi_n^{part} = \text{atan2} \left( \langle r^2 \cos n\phi_{part} \rangle, \langle r^2 \sin n\phi_{part} \rangle \right) + \pi \]

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Differential $v_n$ measurements

- Substantial higher order flow harmonics $v_n$ is observed in both RHIC and LHC energy ranges.
Ridge & $v_n$ in p+Pb collisions

- Ridge and $v_{2,3}$ are observed in high multiplicity p+Pb collision events

Ridge and $v_2$ in d+Au collisions

- Peripheral subtraction at $0.48 < |\Delta \eta| < 0.7$
- None zero $v_2$ is observed in 0-5% d+Au collisions,
  - Similar $p_T$ dependence of $v_2$ in 0-2% p+Pb collisions
  - Consistent with hydrodynamics calculations
Initial or Final State Effect?

- Both initial state (CGC) and final state (hydro) effects can explain $v_n$ in small collisions systems
- Need more constraints by differential measurements
Long-range rapidity correlations

- Muon Piston Calorimeter (MPC) : at $3<|\eta|<4$
- Rapidity separation of $|\Delta \eta|>2.75$ is achieved by measuring correlations between tracks ($|\eta|<0.35$) and MPC towers
Track-tower angular correlations

\[ s(\Delta \phi) = \frac{d(\omega_{tower} N_{track-tower})}{d(\Delta \phi)} 
\]

\[ \Delta \phi = \phi_{tower} - \phi_{track} \]

\[ \omega_{tower} \quad \text{: Transverse Energy of each tower} \]
\[ \text{(Proportional to multiplicity)} \]

\[ N_{track-tower} \quad \text{: Number of Track-Tower Pairs in same events} \]

\[ M(\Delta \phi) \quad \text{: Track-Tower correlations in mixed events} \]

\[ C(\Delta \phi) = \frac{S(\Delta \phi) \int M(\Delta \phi)}{M(\Delta \phi) \int S(\Delta \phi)} \]

\[ : \text{Correlation Function by Event Mixing} \]
Correlations in p+p and 0-5% d+Au collisions

- Ridge is observed in 0-5% d+Au collisions, which is not observed in p+p collisions
“Au-going” & “d-going”

- Ridge is observed in “Au-going” direction
- No ridge is observed in “d-going” direction
- Non-zero $\cos 2\Delta \phi$ is observed in both directions
Centrality dependence in “Au-going” direction

- Ridge is observed only in most-central d+Au collisions
- None-zero $\cos 2\Delta \phi$ is observed in all centralities

arXiv:1404.7461
Centrality dependence in “d-going” direction

- No ridge is observed even in most-central
- None-zero $\cos 2\Delta \phi$ is observed in all centralities, $\cos 2\Delta \phi$ overwhelmed by $\cos 1\Delta \phi$
- What if peripheral subtraction?
- Subtraction method appears to be important when discussing correlation shapes
Ridge across $|\Delta \eta| > 6$

- $E_T$ integrated tower-tower correlations
- Forward-Backward correlations show a ridge across $|\Delta \eta| > 6$!!
- Unlike jet effects
v₂ with more rapidity gap

- EP method using MPC : MPC-CNT rapidity gap |Δη| > 2.75
- Sizable v₂ observed across large rapidity gap
Mass dependence in low $p_T$

Baryon/Meson difference at intermediate $p_T$

Qualitatively consistent with hydrodynamics.
Non-flow effects in p+A collisions

Recoil Jet Subtraction

ATLAS arXiv:1409.1792v1

\[ Y^{\text{sub}}(\Delta \phi) = Y(\Delta \phi) - \alpha Y^{\text{corr}}(\Delta \phi) \]

- \( \alpha \) tuned to completely subtract near-side yield
- Subtraction results in \( v_n = 0 \sim 0.05 \) at high \( p_T \)
- \( \sim 10\% \) reduction of \( v_{2,3} \) at 3 GeV/c
Scaling among p+A and A+A $v_n$

- Scaled $v_n$ in A+A collisions match that in p+A collisions
- Suggests similar origin of $v_n$ in both systems and similar medium response to initial geometry in both systems
Multi Particle Cumulants

- M.P.C is less sensitive to non-flow than 2-part. cum.
- ~10% reduction of $v_2$ in both p+A and A+A collisions
- Convergence in $v_2$\{n=4,6,8,LYZ\} in p+A and A+A collisions
- Consistent with hydrodynamics prediction  

Bzdak et.al. arXiv:1311.7325
that the ratio for the midcentral collisions (other models, e.g., Ref. \[\text{[1304.3403, priv. comm.]}\]) with like centers, Gaussians with different representations of the participating nucleons, point-range correlations in \[\text{compared to peripheral events is well described by a quadru-}\]

- \(v_2/ecc\) vs charged-particle multiplicity (\(\text{d}+\text{Au}, \varepsilon_2(\text{point-like centers}) (\sqrt{s}=200 \text{ GeV})\))
- \(\text{Au+Au, } \varepsilon_2(\text{point-like centers}) (\sqrt{s}=200 \text{ GeV})\)
- \(\varepsilon_2(\text{Gaussian smearing } \sigma = 0.4)\)
- \(\varepsilon_2(\text{disks, } R = 1\text{fm})\)
- \(\text{CMS Pb+Pb } v_2/\varepsilon^\text{part} (\sqrt{s}=2.76 \text{ TeV})\)
- \(\text{CMS Pb+Pb } v_2/\varepsilon_2 (\sqrt{s}=2.76 \text{ TeV})\)
- \(\text{ATLAS p+Pb (}\sqrt{s}=5 \text{ TeV})\)
- \(\text{ALICE p+Pb (}\sqrt{s}=5 \text{ TeV})\)

\(\langle p_T \rangle \approx 1.4 \text{ GeV/c}\)
HBT Methodology

Space momentum correlation

\[ C_2 = \frac{P(p_1, p_2)}{\{P(p_1)P(p_2)\}} \sim 1 + |\rho(q)|^2 \]

\[ = C_2^{\text{core}} + C_2^{\text{halo}} \]

\[ = [\lambda(1 + G)F_{\text{coul}}] + [1 - \lambda] \]

\[ G = \exp\left(-R_s^2q_s^2 - R_o^2q_o^2 - R_L^2q_L^2 - 2R_{os}^2q_oq_s\right) \]

\( F_{\text{coul}} \) : coulomb correction factor
\( \lambda \) : fraction of pairs in the core
\( s \) : (sideward) geometrical size
\( o \) : (outward) geometry and time duration
\( L \) : (longitudinal) beam direction
\( os \) : outward-sideward cross term
Event selections of d+Au and Au+Au collisions for HBT Analysis

**Bjorken energy density vs N_{part}**

\[ \varepsilon_{\text{Bj}} = \frac{1}{\pi R_c^2} \frac{dE_T}{d\eta} \]

**Initial Parameters for peripheral Au+Au and central d+Au**

<table>
<thead>
<tr>
<th></th>
<th>N_{part}</th>
<th>dE_T / d\eta</th>
<th>\bar{R}</th>
<th>\varepsilon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au</td>
<td>16.7±1.1</td>
<td>19±1.5</td>
<td>0.71</td>
<td>0.5</td>
</tr>
<tr>
<td>d+Au</td>
<td>15.7±1.6</td>
<td>22±1.5</td>
<td>0.44</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Glauber Model initial size**

\[ \frac{1}{\bar{R}} = \sqrt{\left( \frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2} \right)} \]

\( \sigma_x \& \sigma_y \rightarrow \text{RMS widths of density distribution} \)

Slide from N.Ajit QM’14

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HBT correlation in d+Au & Au+Au

- $\pi^+\pi^+$ HBT correlations measured at similar $N_{\text{part}}$ & $k_T$

<table>
<thead>
<tr>
<th>System</th>
<th>$N_{\text{part}}$</th>
<th>$&lt;k_T&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au</td>
<td>16.7±1.1</td>
<td>0.39</td>
</tr>
<tr>
<td>d+Au</td>
<td>15.7±1.6</td>
<td>0.39</td>
</tr>
</tbody>
</table>

- HBT correlations in d+Au larger than those in Au+Au imply smaller HBT radii
m_T dependence in d+Au & Au+Au

0.2 0.3 0.4 0.5 0.6 0.7
m_T (GeV/c)

<table>
<thead>
<tr>
<th>R_{out}</th>
<th>R_{side}</th>
<th>R_{long}</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 GeV (π^+π^-)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Au+Au (60-88%) | d+Au (0-10%) | Au+Au systematic unc. | d+Au systematic unc. |

- Qualitatively similar m_T dependence in d+Au & Au+Au
- Similar expansion dynamics?
- Blast-wave fitting defined by expansion velocity & freeze-out temperature works well for R_{side}

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Emission duration & freeze-out volume

\[ \frac{R_{\text{out}}}{R_{\text{side}}} \approx 1 \]

Short emission duration

Freeze-out Volume

\[ v(\text{dAu}) < v(\text{Au+Au}) \]

Similar \( m_T \) dependence

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**Diagram**

- **Panel (a)**: \( \sqrt{s_{NN}} = 200 \text{ GeV} (\pi^+\pi^+ \& \pi^-\pi^-) \)
  - Red circles: \( \text{Au+Au (60-88\%)} \)
  - Blue triangles: \( \text{d+Au (0-10\%)} \)
  - Yellow band: systematic error
  - Green band: systematic error

- **Panel (b)**: Ratio \( \frac{R_{\text{out}}}{R_{\text{side}}}, \frac{R_{\text{side}}}{R_{\text{long}}} \) vs. \( m_T \) (GeV/c)
  - Red circles: \( \text{Au+Au (60-88\%)} \)
  - Blue triangles: \( \text{d+Au (0-10\%)} \)
  - Yellow band: systematic error
  - Green band: systematic error

- **Panel (c)**: Ratio vs. \( m_T \) (GeV/c)
  - Black circles: systematic error

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[arXiv:1404.5291]
HBT radii as a function of $N_{\text{part}}^{1/3}$

- $d+Au$ & $Au+Au$ HBT radii do not scale together but show a similar linearity
- $p+p$ at 7 TeV also show a linearity with respect to $<dN_{\text{ch}}/\eta>^{1/3}$
Initial R dependence in p+A & A+A collisions

Glauber MC to obtain initial size $R$ vs $N_{\text{part}}$

$$\frac{1}{R} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

$\sigma_x \sigma_y$: RMS width of density distribution

- Linearity and good scaling are seen in p+A and A+A collisions
- Implies possible radial expansion in p+A systems
Event-by-Event Fluctuations of $v_n$

**LHC Data**

**Hydro Calculation**

- Eve-by-Eve fluctuation seems to be independent of shear-viscosity
- Possible probe to access IC
**Event-Shape Engineering**

Schukraft et.al: arXiv:1208.4563

ATLAS Preliminary

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

\[ L_{\text{int}} = 7 \mu \text{b}^{-1} \]

Pb+Pb

- \(|q_n|: \text{Strength of Flow}\]

\[ (q_n^x, q_n^y) = \frac{1}{\sum_i \cos n \phi_i, \sum_i \cos n \phi_i} \]

\[ |q_n| = q_n^x + q_n^y \]

- Possible control of initial geometry

AMPT J.Jia et.al : arXiv:1403.6077

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$v_n(n=2,3,4,5)$ vs $q^2$

- $q^2$ dependence for $v_2$
- Weaker, but $q^2$
  dependence also for $v_n(n=3,4,5)$

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$v_n(n=2,3,4,5)$ vs $q_2$
**V2 - V3 correlations**

- **Negative-correlations between v2 and v3**  \( v_3 = c_0 + c_1 v_2 \)

- **Linear response to initial geometry**

\[
v_2 e^{i2\Phi_2} = a_0 \epsilon_2 e^{i2\Phi_2^*} \quad \quad \quad \quad v_3 e^{i3\Phi_3} = a_0 \epsilon_3 e^{i3\Phi_3^*}
\]

- **Anti correlations at initial eccentricities?**

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V$^2$ - V$^4$ correlations

- Linear-term and non-linear term
- Clear non-linear term is seen in data: upward bending

\[ v_4 e^{i 4 \Phi_4} = a_0 e^{i 4 \Phi_4^*} + a_1 (\epsilon_2 e^{i 2 \Phi_2^*})^2 + \ldots \]
\[ = c_0 e^{i 4 \Phi_4^*} + c_1 (v_2 e^{i 2 \Phi_2^*})^2 + \ldots \]

\[ v_4 = \sqrt{c_0^2 + c_1^2 v_2^4} \]
\[ v_2 - v_n \] correlations

- Compared with Glauber and MC_KLN \( \varepsilon_2 - \varepsilon_n \) correlations
- Access to IC if a unique hydro response to a given initial correlation
Linear/non-Linear terms

\[ v_4^L = c_0, \quad v_4^{NL} = \sqrt{v_4^2 - v_4^L^2} \]
\[ v_5^L = c_0, \quad v_5^{NL} = \sqrt{v_5^2 - v_5^L^2} \]

- Most-central: \( v_4 \) is almost independent of \( v_2 \)
- NL term increases with centrality
- Similar trends in \( v_5 \)
Viscous dumping

- Viscous dumping of $v_n$ with “n”

**PRC85.024901**

![Graph](image)

- Acoustic viscous dumping

$$\delta T_{\mu\nu}(n,t) = \exp(-\beta' n^2) \delta T_{\mu\nu}(n,0), \quad \beta' = \frac{2\eta}{3sR^2T},$$

Lacey et.al. 1105.3782, Staig et. al. PRC84.034908

- Dumping pattern may be determine by the data
Twist Effect

- Twisted medium between forward and backward directions emerging from participant fluctuations
- Correlation length of initial fluctuations in rapidity directions
- Possible underestimate of $v_n$ i.e. overestimate of shear-viscosity due to neglecting decorrelated term
AMPT: Twist Effect

- Event-Plane & Ecc & $q_{2,3}$ determination
  \[ F : +4 < \eta < +6 \]
  \[ M : -1 < \eta < +1 \]
  \[ B : -6 < \eta < +4 \]

- Correlations among EP, ECC, $q_{2,3}$ etc.

- Final twist probes initial twist

Jia et. al. arXiv:1403.6077

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AMPT : Twist Effect

Event Selection

\[ 2(\Psi_2^F - \Psi_2^B) > 0.5 \quad \varepsilon_2^{\text{back}} < \varepsilon_2^{\text{for}}. \]

\[ 3(\Psi_3^F - \Psi_3^B) > 1.5 \quad \varepsilon_3^{\text{back}} < \varepsilon_3^{\text{for}}. \]

\[ v_n^c = \left< \cos n(\phi - \Psi_n) \right> / \text{Res} \{ n\Psi_n \} \]

\[ v_n^s = \left< \sin n(\phi - \Psi_n) \right> / \text{Res} \{ n\Psi_n \} \]

- Twisted term \( v_n^s \) observed
  - i.e. underestimate of \( v_n \)
- This study should be done for experimental data
Summary

- Similar trends among $p(d)+A$ and $A+A$ collisions in $v_n$ and HBT measurements
- Observables in $p(d)+A$ collisions are qualitatively consistent with final state effects
- Hadron mass dependence of CGC?
- Event Shape Control Study is a promising method to address initial geometry of heavy ion collisions
- Possible access to initial state model
Auxiliary Slides
Hydro models associate a larger expansion time with a larger initial size $\overline{R}$. Does it make a good scaling parameter?

Use Glauber model to get

$$N_{\text{part}}^{1/3} \propto \text{initial size } \overline{R}$$

$$\frac{1}{\overline{R}} = \sqrt{\left(\frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2}\right)}$$

$\sigma_x$ & $\sigma_y \rightarrow$ RMS widths of density distribution

Pion HBT radii scale with $\overline{R}$

Linear dependence of transverse expansion on initial geometry

Slide from N.Ajit QM’14
The non-linear & linear components from EP correlations are obtained as:

\[ v_4^{NL} = v_4 \langle \cos 4(\Phi_2 - \Phi_4) \rangle, \quad v_4^L = \sqrt{v_4^2 - (v_4^{NL})^2} \]

The results from the two procedures compare quite well.

In most central cases almost all \( v_4 \) is uncorrelated with \( v_2 \).

Correlated component gradually increases and overtakes linear component as \( N_{\text{part}} \sim 120 \).
**v_5-v_2** correlations: comparison to EP correlations

- Compare linear & non-linear components from this analysis to EP correlation results

- The non-linear & linear components from EP correlations are obtained as:

\[
v_5^{NL} = v_5 \langle \cos(2\Phi_2 + 3\Phi_3 - 5\Phi_5) \rangle, \quad v_5^L = \sqrt{v_5^2 - (v_5^{NL})^2}
\]