Signatures of collectivity in small systems observed by PHENIX

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Hydrodynamical model calculation of the small collision systems shows collective behavior.

The initial geometry effect propagates to the final stage.
Initial geometry and the $v_n$

The hierarchy of $v_2$ and $v_3$ consistent with that of $\varepsilon_n$.

The hierarchy of $v_2$ and $v_3$ consistent with that of $\varepsilon_n$. Initial geometry dependence of $v_2$ is studied using different collision systems.
Hydrodynamic model calculations are showing the best agreement with the $v_n$ measurements in 3 collision systems ($p/d/^3\text{He}+\text{Au}$).
\( v_2 \) and the \( dN_{ch}/d\eta \) scaling

In larger systems (d+Au and \(^3\)He+Au) the \( dN_{ch}/d\eta \) and \( v_2 \) rapidity dependence have the same shape.

In smaller systems (p+Au) deviations are observed near the event plane detector.

Is there some non-flow or other effect?
Method comparison

1. Published data with the event plane detector
2. Two-particle correlation reconstructs the same results (no nonflow estimation in the systematic uncertainties)

**Graphical Presentation**

- **p+Au 200 GeV, h^±, |η|<0.35, 0-5%**
- **v_2(EP), PRC 95, 034910**
- **v_2(2PC), -4<|η|<-3, -3<|η|<-1, |η|<0.35**
  - Nonflow is not estimated

**Legend**

- BBCS
- FVTX S
- CNT
- FVTX N
- BBCN

**PHENIX PRC**: BBCS-FVTXS-CNT
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4. PHENIX can reconstruct the STAR result choosing the same kinematics.
Multi-particle correlation

- two-, four-particle angular correlations
- Multi-particle correlation suppress the nonflow

\[ v_2 \{2\} = \left( v_2^2 + \sigma^2 + \delta^2 \right)^{1/2} \quad : \quad \text{fluctuation + nonflow effect} \]

\[ v_2 \{4\} \approx v_2 \{6\} \approx \left( v_2^2 - \sigma^2 \right)^{1/2} \quad : \quad \text{fluctuation} \]

\[ v_2 \{4\} = (-c_2 \{4\})^{-1/4} \]

Multi-particle correlation provide information how the event-by-event flow fluctuating
Correlations in d+Au

• two-, four-particle angular correlations

$v_2\{2\}$, $v_2\{2, |\Delta \eta| > 2\}$, $v_2\{4\}$, $v_2\{6\}$ show the collective behavior in high-multiplicity events.
Correlations & fluctuations in p/d+Au

- $v_2\{4\}^2 \approx \langle v_2 \rangle^2 - \sigma^2$
  - $c_2\{4\}$ in p+Au is dominated by fluctuations
- AMPT (A Multi-phase transport model) describes the sign
Initial eccentricity distributions

Monte-Carlo Glauber

Initial eccentricity distribution is highly non-Gaussian

Fluctuations are highly non-trivial in small systems.

\[ \langle \varepsilon^2 \rangle = 0.27, \sigma = 0.14, s = 0.51, k = 2.86 \]

\[ \langle \varepsilon^2 \rangle = 0.56, \sigma = 0.24, s = -0.16, k = 1.97 \]
Sub-event cumulant method

• To investigate further effect of
  – the suppressing the nonflow
  – the role of the fluctuations

• Expected nonflow contaminations: \( aa | bb < ab | ab < \) standard method

\[
\langle\langle 4 \rangle\rangle = \left\langle\left\langle e^{i\phi_a} (\phi_a + \phi_a - \phi_b - \phi_b) \right\rangle\right\rangle
\]
Sub-event cumulant method

• To investigate further effect of
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• Expected nonflow contaminations: \( aa|bb < ab|ab < \) standard method

\[ \langle\langle 4 \rangle\rangle = \langle\langle e^{in}(\phi_a + \phi_b - \phi_a - \phi_b) \rangle\rangle \]
Sub-event cumulant in p+Au

c\textsubscript{2}\{4\} remains positive in sub-event selections

The origin could be attributed to the fluctuations

- Poster by Qiao Xu
Summary

• Collective behavior was observed in small systems by the PHENIX experiment
  – Measured $v_n$ are well described by viscous hydro model
  – Confirmed initial geometry effect in the medium formed in small systems ($p/d/^{3}$He + Au)

• Systematic studies of non-flow and fluctuation dependencies
  – The $v_2\{2\text{PC}\}$ reconstructed in different kinematics
  – Small variance limit breaks in p+Au and in d+Au collisions
  – Flow fluctuations are significant in $c_2\{4\}$ in p+Au collisions confirmed by sub-event cumulant analysis
THANK YOU
Comparison with STAR

1. Published data with the event plane detector
2. 2-particle correlation reconstructs the same results (no nonflow estimation in the systematic uncertainties)
3. STAR 2-particle result shows systematically larger $v_2$ (no nonflow estimation either)
4. PHENIX can reconstruct the STAR result choosing the same kinematics.

Add as animation

$\phi$ $^+$ $^{197\text{Au}} + \phi$, $h\eta < 0.35$, 0-5%

$\diamondsuit v_2^{\{EP\}}$, PRC 95, 034910

$\square v_2^{\{2PC\}}$, $-4 < \eta < -3$, $-3 < \eta < -1$, $h\eta < 0.35$

$\star v_2^{\{2PC\}}$, $-3 < \eta < -1$, $h\eta < 0.35$, $1 < \eta < 3$

$\star$ STAR prelim. $v_2^{\{2PC\}}$, 0-10%, $|\Delta \eta| > 1$

PHENIX preliminary

$V_2$

$P_T^{\text{CNT}}[\text{GeV/c}]$

PHENIX: BBCS-FVTXS-CNT

STAR prelim.: FVTXS-CNT-FVTXN

Add as animation
Multi-particle correlation

- two-, four-particle angular correlations

- BBCS
- FVTX S
- CNT
- FVTX N
- BBCN

-4 -3 -2 -1 0 1 2 3 4

- Au - going
- p/d/\(^3\)He - going
Initial geometry and multiplicity

The $dA$ shows larger $v2$, the initial eccentricity carries into the final result.

Comparison of $dA$ and $pA$ at same multiplicity
The new PHENIX results are in good agreement with the previous PHENIX results (Run 8) at the mid-rapidity.
The new PHENIX results are in **good agreement** with the previous PHENIX results (Run 8) at the mid-rapidity.

Also the $dN_{ch}/d\eta$ measured at the wider range of rapidity by using the FVTX.

**Good agreement with PHOBOS data**
Multi-particle correlation

- two-, four-particle angular correlations

\[ \langle 2 \rangle = \langle \cos(n(\phi_1 - \phi_2)) \rangle = \langle v_n^2 \{2\} \rangle \]

\[ v_n^2 \{2\} = \left( v_n^2 + \sigma^2 + \delta^2 \right)^{1/2} \]

Average over particles in a single event

Nonflow Fluctuations

Multi-particle correlation

- two-, four-particle angular correlations

\[ \langle 4 \rangle = \langle \cos(n(\phi_1 + \phi_2 - \phi_3 - \phi_4)) \rangle = \langle v_n^2 \rangle \]

\[ v_2 \{4\} \approx \left(v_2^2 - \sigma^2\right)^{1/2} \]

Negligible nonflow is expected

Fluctuations
Multi-particle correlation

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This changing derives smaller $|\Delta \eta|$ between the tracks.
Multi-particle correlation

- two-, four-, six-particle angular correlations

\[ \langle 6 \rangle = \langle \cos(n(\phi_1 + \phi_2 + \phi_3 - \phi_4 - \phi_5 - \phi_6)) \rangle = \langle v_n^2 \rangle \]

\[ c_n \{6\} = \langle \langle 6 \rangle \rangle - 9 \langle \langle 4 \rangle \rangle \langle \langle 2 \rangle \rangle + 12 \langle \langle 2 \rangle \rangle^3 = 4[\{ v_n \{6\} \}]^6 \]
Multi-particle correlation

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\[ v_2 \{4\} \approx v_2 \{6\} \approx \left( v_2^2 - \sigma^2 \right)^{1/2} \]
Multi-particle correlation

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\[ \langle 2 \rangle = \langle \cos(n(\phi_1 - \phi_2)) \rangle = \langle v_n^2 \{2\} \rangle \]

\[ \langle \langle 2 \rangle \rangle = c_n \{2\} = [v_n \{2\}]^2 \]

Average over particles in a single event

1. Average over particles in a single event
2. Average over events