Discovering a new flow phenomena of flow angle and flow magnitude fluctuations and its impact on QGP studies

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Anisotropic flow

- QGP created in heavy-ion collisions can be probed via anisotropic flow
- Initial spatial anisotropy is transferred via large pressure gradients to final state momentum anisotropy

\[ \frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} \vec{V}_n e^{in\phi} \]

- Comparing data with theoretical models allow for extraction of QGP properties
Flow vector fluctuations

Flow vector may fluctuate with transverse momentum, $p_T$

$$\vec{V}_n = v_n e^{i n \Psi_n}$$

- $v_n$: Anisotropic flow
- $\Psi_n$: Flow symmetry plane angle

Both $v_n$ and $\Psi_n$ may fluctuate with $p_T$!

Hydro model predicted additional flow angle and flow magnitude fluctuations

Cannot be disentangled with current observables based on 2-particle correlations

**Unique to hydro models?**

Scan of observables sensitive to flow vector fluctuations with A Multi-Phase Transport model (AMPT)
Flow vector fluctuations

\[ v_n \{2\} \] measures particle of interest against reference flow

\[ v_n[2] \] takes two particles from same \( p_T \) bin

Ratio of the two → sensitive to the \( p_T \)-dependent flow vector fluctuations

\[ \frac{v_n \{2\}}{v_n[2]} = \frac{\langle v_n(p_T^q) \rangle}{\sqrt{\langle v_n^2(p_T) \rangle}} \cos n[\Psi_n(p_T^q) - \Psi_n] \] → Flow angle fluctuations

\[ \sqrt{\langle v_n^2(p_T) \rangle} \langle v_n^2 \rangle \] → Flow magnitude fluctuations

\[ v_2 \{2\}/v_2[2] < 1 \] → Flow vector fluctuations

How to disentangle the two effects?
Factorisation ratio

Factorisation of two-particle correlation into two single-particle distributions

\[ V_{n\Delta}(p_T^a, p_T^t) = v_n(p_T^a) \times v_n(p_T^t) \]

Test above relation with factorisation ratio

\[ r_n = \frac{\langle v_n(p_T^a) v_n(p_T^t) \cos n[\Psi_n(p_T^a) - \Psi_n(p_T^t)] \rangle}{\sqrt{\langle v_n^2(p_T^a) \rangle} \sqrt{\langle v_n^2(p_T^t) \rangle}} \]

\[ r_2 < 1 \rightarrow \text{Factorisation is broken} \]

Factorisation broken in hydrodynamics due to fluctuations in the initial state

\[ F. G. Gardim et al., PRC 87 (2013) 3, 031901 \]
Experimental measurements

Measurements by ALICE indicate the presence of $p_T$-dependent flow vector fluctuations.

Well described by hydro calculations

- Deviations from unity of $v_2(2)/v_2(2)$ in central collisions → $p_T$-dependent $V_2$ flow vector fluctuations
- Deviations are largest at the edge of hydro $p_T$ range
- High precision Run 2 measurements allow for improved constraints on future model comparisons
A Multi-Phase Transport model (AMPT)

1. Initial conditions are generated with HIJING
   *Lund string parameters, a and b, related to string tension* $\kappa$
   
   $\kappa \propto \frac{1}{b(2 + a)}$

2. Convert hadrons produced from string fragmentation into valence quarks and anti-quarks

3. Parton-parton interaction are treated with Zhang’s Parton Cascade
   *Cross section obtained from pQCD screening masses*
   
   $\sigma_{gg} = \frac{9\pi\alpha_s^2}{2\mu^2}$

4. Quark coalescence model convert partons into hadrons

5. Hadronic rescattering is handled by A Relativistic Transport (ART) model
A Multi-Phase Transport model (AMPT)

Test observables sensitive to $p_T$-dependent flow fluctuations with different configurations of the AMPT model

- Probe effect of **transport properties** by changing the cross section (Par1 vs Par4, Par2 vs Par5)

<table>
<thead>
<tr>
<th></th>
<th>Cross section</th>
<th>a</th>
<th>b</th>
<th>ART</th>
</tr>
</thead>
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<tr>
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<td>0.3</td>
<td>0.15</td>
<td>ON</td>
</tr>
<tr>
<td>Par2</td>
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<tr>
<td>Par5</td>
<td>3mb</td>
<td>0.3</td>
<td>0.15</td>
<td>OFF</td>
</tr>
</tbody>
</table>

- Probe effect of **hadronic rescattering** by turning ART off (Par1 vs Par2, Par4 vs Par5)

- Probe effect of **initial conditions** by changing Lund string parameters $a$ and $b$ (Par2 vs Par3)
\[ v_2^2 / v_2^2 \]

Deviation from unity in AMPT
→ \( p_T \)-dependent flow vector fluctuations

Small (max. 10%) difference due to cross section
Larger shear viscosity dampen initial state fluctuations

ART ON decreases the deviation from unity (max. 20%)
Smaller anisotropic flow increases relative contribution from initial state

Large effect from changing initial state parameters (~ 40%)
Flow vector fluctuations originating in fluctuating initial conditions

ALICE data slightly overestimated
Increasing factorisation ratio, $r_2$

The breaking of factorisation depend on the difference in transverse momentum $|p_T^a - p_T^t|$.

Factorisation is broken for all configuration

*Large sensitivity to the variation in the Lund string parameters*
Flow angle and magnitude fluctuations

- Observable to measure flow angle fluctuations:

\[ A_n^f = \frac{\langle \langle \cos[n(\varphi_1^a + \varphi_2^a - \varphi_3^a - \varphi_4^a)] \rangle \rangle}{\langle \langle \cos[n(\varphi_1^a + \varphi_2^a - \varphi_3^a - \varphi_4^a)] \rangle \rangle} \]

\[ = \frac{\langle v_n^2(p_T^a) v_n^2 \cos 2n[\Psi_n(p_T^a) - \Psi_n] \rangle}{\langle v_n^2(p_T^a)v_n^2 \rangle} \]

\[ \approx \langle \cos 2n[\Psi_n(p_T^a) - \Psi_n] \rangle \]

\[ A_n^f < 1 \text{ indicates } p_T\text{-dependent flow angle fluctuations} \]

- Observable to measure flow magnitude fluctuations

\[ \frac{\langle \langle \cos n(\varphi_1^a + \varphi_2^a - \varphi_3^a - \varphi_4^a) \rangle \rangle}{\langle \langle \cos n(\varphi_1^a - \varphi_3^a) \rangle \rangle \langle \langle \cos n(\varphi_2 - \varphi_4) \rangle \rangle} = \frac{\langle v_n^2(p_T^a) v_n^2 \rangle}{\langle v_n^2(p_T^a) \rangle \langle v_n^2 \rangle} \]

- Normalise with \( p_T \)-integrated baseline:

\[ M_n^f = \frac{\langle v_n^2(p_T^a) v_n^2 \rangle / \langle v_n^2(p_T^a) \rangle \langle v_n^2 \rangle}{\langle v_n^4 \rangle / \langle v_n^2 \rangle^2} \]

\[ M_n^f < 1 \text{ indicates } p_T\text{-dependent flow magnitude fluctuations} \]
New ALICE measurements

Recent measurements by ALICE
→ Observation of flow angle and flow magnitude fluctuations

Largest deviation in central collisions
Dominated by event-by-event fluctuations

Phenomena present in transport model?
What is the origin of the flow angle and flow magnitude fluctuations

Flow angle fluctuations

Isolate the fluctuations of $\Psi_2$ with $A_2^f$ observable

No effect from varying the cross section

*Any effect is expected to show at high $p_T$ - large uncertainty*

Turning ART off increases flow angle fluctuations (max. 20%)

Very sensitive to initial conditions (~60%)

*Event-by-event fluctuations in initial state*

AMPT overestimates the flow angle fluctuations

Emil Gorm Nielsen et al., to be submitted
Flow magnitude fluctuations

Isolate the fluctuations of $v_2$ with $M_2^f$

No effect from varying the cross section

*Dependence on transport properties cancelled by ratio*

Only small effect (~10%) from turning ART off in highest $p_T$ bin

Largest effect from changes in initial conditions

*Highly sensitive to the initial conditions*

ALICE data is well described by AMPT
The $p_T$-dependent flow vector, flow angle and flow magnitude fluctuations present in transport model
Not unique feature of hydrodynamic models

The observables show most sensitivity to changes to the initial conditions
The $p_T$-dependent flow fluctuations are primarily driven by event-by-event fluctuations in the initial state

The AMPT model can reasonably reproduce the observed fluctuations in data
AMPT mostly overestimates the fluctuations