Searches for \( p_T \) dependent fluctuations of flow angle and magnitude in Pb-Pb and p-Pb collisions

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(On behalf of the ALICE Collaboration)
Traditionally Flow analyses look for correlations w.r.t. common symmetry planes over a large range in $p_T$.

- Constraints on the initial state and $\eta/s$.

*Initial symmetry planes*  

*Final symmetry planes ??*
Traditionally Flow analyses look for correlations w.r.t common
symmetry planes over a large range in $p_T$.

However, recent hydrodynamic simulations show $p_T$ dependent flow
angle and magnitude fluctuations
- Further constraints on the initial state and $\eta/s$.

Initial symmetry planes

$\Phi_2$  $\Phi_3$  $\Phi_4$

Final symmetry planes ??

$\psi_{2}(p_T)$  $\psi_3(p_T')$  $\psi_{4}(p_T)$  $\psi_4(p_T)$

2 particle correlations probe these predicted effects in experiments.
2 Particle Correlations

- **Type < a, All >**
  - One particle from \( p_T^a \), the other from entire \( p_T \)
  - \( d_n\{2\} \)

- **Type < All, All >**
  - Two particles from entire \( p_T \)
  - \( c_n\{2\} \)

- **Type < a, b >**
  - One particle from \( p_T^a \), the other from \( p_T^b \)
  - \( V_{n\Delta}(p_T^a, p_T^b) \)

- **Type < a, a >**
  - Two particles from \( p_T^a \)
  - \( \nu_n[2] \)
  - \( V_{n\Delta}(p_T^a, p_T^a) = \nu_n[2]^2 \)
\( v_n^2 \) and \( v_n[2] \)

- \( v_n^2 = d_n^2/c_n^2 \)
  - \( <a, \text{All}> \) for \( d_n^2 \) and \( <\text{All}, \text{All}> \) for \( c_n^2 \)
  - Contributions from possible \( p_T \) dependent flow angle and magnitude fluctuations, in addition from non-flow

- \( v_n[2] \):
  - \( <a, a> \)
  - Contributions from non-flow

- Ratio of \( v_n^2/v_n[2] \): \( <a, \text{All}> \rightarrow <\text{All}, \text{All}>&<a, a> \)

Factorization ratio $r_n$

- $r_n$ probes $<a, b> \rightarrow <a, a> \& <b, b>$
- $r_n < 1$, Factorization broken

$r_n$ observed in hydrodynamic calculations
- indication of $p_T$ dependent fluctuations of flow angle and magnitude.
Analysis Details

Data sample:
- Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV
  - $\sim 12$ M events analyzed
- p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV
  - $\sim 96$ M events analyzed

Tracks used:
- $-0.8 < \eta < 0.8$
- $0.2 < p_T < 6.0$ GeV/c

Detectors used:
- **Inner Tracking System** (trigger, tracking and vertexing)
- **Time Projection Chamber** (tracking, centrality determination)
- **V0 detectors**
  - $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$
  - (trigger, centrality determination)
**v_2^{(2)} and v_2^{[2]}**

- MC-KLN works better for both $v_2^{[2]}$ and $v_2^{(2)}$ up to higher $p_T$. 

**MC-Glauber & MC-KLN:** PRC 87, 034913  

**IP-Glasma:** PRL 110, 012302
Significant deviation for $p_T > 2$ GeV/c in most central collisions.

Hydrodynamic calculations (no non-flow) already overestimate the deviation of $v_2\{2\}/v_2[2]$ in most central collisions
- Calculations with MC-KLN describe the data better than MC-Glauber.
Breakdown of factorization more pronounced in central collisions.

Hydrodynamic calculations also show that the factorization is broken.

CMS $r_2(|\Delta\eta| > 2.0)$ quantitatively agrees with our measurements

- Additional $\eta$ dependent fluctuations of flow angle ($\Psi_2$) and/or magnitude ($v_2$) are not observed or non-flow is similar between $|\Delta\eta| > 0.8$ and 2.0.
**v₃ and v₄**

**MC-Glauber & MC-KLN:** PRC 87, 034913

**IP-Glasma:** PRL 110, 012302


- **Hydrodynamic calculations:**
  - with IP-Glasma agree vₙ[2] very well, interesting to test if it can reproduce vₙ[2].
  - with MC-KLN or MC-Glauber do not describe the pₜ dependence of v₃ or v₄.
In data no clear indication of $p_T$ dependent fluctuations of flow angle ($\Psi_3$, $\Psi_4$) and magnitude ($v_3$, $v_4$).

These effects seem more pronounced in hydrodynamic calculations.
r\textsubscript{3} consistent with 1 up to |p\textsubscript{T}^a-p\textsubscript{T}^\tau| \sim 3 \text{ GeV}/c.

- Good agreement between ALICE and CMS measurements.
  - No clear contribution from additional $\eta$ dependent fluctuations of flow angle ($\Psi_3$) and magnitude ($v_3$) or non-flow.

Hydrodynamic calculations seem to overestimate the effect.
$v_2$ and $v_3$ in p-Pb

Flow in p-Pb? See talks: L. Milano (Tuesday, 14:40)

- $v_2[2]$ and $v_2\{2\}$ deviate at $p_T \sim 3$ GeV/c for presented multiplicity classes.

- No clear difference between $v_3[2]$ and $v_3\{2\}$ for the presented $p_T$ range.
\textbf{v}_2 \text{ and } \textbf{v}_3 \text{ in p-Pb}

- \textbf{Hydrodynamic calculations works better in central than peripheral p-Pb collisions.}

- \textbf{No clear difference between } \textbf{v}_3[2] \text{ and } \textbf{v}_3\{2\} \text{ for the presented } p_T \text{ range.}
Factorization is always significantly broken in p-Pb collisions (in case there is no non-flow subtraction).

Factorization is valid for a wider $p_T$ range in peripheral Pb-Pb collisions.
We presented $v_n\{2\}$, $v_n[2]$, ratio of $v_n\{2\}/v_n[2]$ and $r_n$ in Pb-Pb collisions.

- We observed indications of $p_T$ dependent flow angle ($\Psi_2$) and magnitude ($v_2$) fluctuations, however non-flow contributions are not fully excluded.
- The $p_T$ dependent fluctuations of the flow angle and magnitude seem to be smaller than what hydrodynamic predictions.

- Factorization is more strongly broken in p-Pb collisions
  - Different from peripheral Pb-Pb collisions.
  - Further study on non-flow are necessary.

Thanks for your attention!
Without η gap, \( r_2 \) deviates from unity for entire \( p_T \) range

With η gap

- Consistent results for \(|Δ\eta|>0.4\) and \(|Δ\eta|>0.8\).
- Factorization is broken as \(|p_T^t - p_T^a|\) increase.
\( \Delta \eta \) dependence of \( v_2 \) in Pb-Pb

- **\( v_2 \{2\} \) and \( v_2 [2] \)**
  - decrease when the \( \Delta \eta \) increase;
  - The short range correlations (non-flow) are expected to be suppressed when applying \( \Delta \eta \) gap.
Without $\eta$ gap, $r_2$ deviates from unity

With $\eta$ gap

- Consistent results for $|\Delta \eta|>0.4$ and $|\Delta \eta|>0.8$, non-flow effects are suppressed
- The factorization is valid when $p_T^a \sim p_T^c$ and broken stronger as $|p_T^c-p_T^a|$ increase
  - Can be explained by $p_T$ dependent flow magnitude fluctuations, as well as by non-flow probably.
The short range correlations (non-flow) are expected to be suppressed when applying $\Delta \eta$ gap.

- $v_2 \{2\}$ and $v_2[2]$
  - decrease when the $\Delta \eta$ increase;
  - The short range correlations (non-flow) are expected to be suppressed when applying $\Delta \eta$ gap.
\( V_{n\Delta} \) via \( Q \)-cumulant method

- \( V_{n\Delta} \) is a product of \( Q^a_n \) and \( Q^{b*}_n \) scaled by corresponding multiplicities in certain \( p_T \) bin in each sub-event.

\[
V_{n\Delta}(p_T^a, p_T^b) = \langle V_n^a V_n^{b*} \rangle = \langle v_n^a v_n^b \cdot e^{in(\Psi_n^a - \Psi_n^b)} \rangle
\]

\[
V_{n\Delta}(p_T^a, p_T^b) = \left\langle \frac{Q_n^a \cdot Q_n^{b*}}{M_a M_b} \right\rangle
\]

\[
Q_n = \sum_{i=1}^{N} e^{in \phi_i} \quad : \text{Flow-vector}
\]

- \( Q_n^a \) and \( Q_n^b \) from \( p_T^a \) and \( p_T^b \)

\[
V_{n\Delta}(p_T^a, p_T^{a'}) = \left\langle \frac{Q_n^a \cdot Q_n^{a'*}}{M_a M_a'} \right\rangle
\]

Here \( Q_n^a \) and \( Q_n^{a'} \) (\( Q_n^b \) and \( Q_n^{b'} \)) from same \( p_T \) range but different sub-events.

\[
V_{n\Delta}(p_T^b, p_T^{b'}) = \left\langle \frac{Q_n^b \cdot Q_n^{b'*}}{M_b M_b'} \right\rangle
\]

- If the main goal of using two-particle correlation is to obtain \( V_{n\Delta} \), using modified \( Q \)-Cumulant method is a direct and efficient way.

Comparison to published results

**Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV**

- ALICE Preliminary
- Centrality: 30-40%
- $|n| < 0.8$

**Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV**

- ALICE Preliminary
- Centrality: 40-50%
- $|n| < 0.8$

**V0A Multiplicity Event Class (Pb-side) (%)**

- 0-20 %
- $v_2(2)$ [2PC, $|\Delta n| > 0.8$] (PLB 726, 164)
- $v_2(2)$ [$|\Delta n| > 0.8$]

**p-Pb $\sqrt{s_{NN}} = 5.02$ TeV**

- ALICE Preliminary
The definition of “centrality” might be different in ALICE and hydrodynamic calculations (MUSIC).