Directed flow measurement in Pb-Pb collisions with ALICE at the LHC

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Introduction:

Collective flow in heavy-ion collisions
Directed flow ($v_1$) measurements

Results:

Comparison to RHIC and Monte-Carlo event generators
$v_1 (\eta)$, $v_1 (p_t)$, $v_1 (\text{centrality})$
$v_1$ fluctuations

Conclusions
Collective anisotropic flow in heavy-ion collisions

The angular distribution of the produced particles reflects the special asymmetry of the nuclei overlap zone due to the interactions among the constituents of the produced matter.

\[ E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_{RP})) \right) \]

Flow components \( v_n \):
\[ v_n = \langle \cos\left(n(\phi - \Psi_{RP})\right) \rangle \]

Where \( \Psi_{RP} \) is a reaction plane, which is not known and estimated experimentally.

Directed flow \( v_1 \):
- Probes the system at early time
- Sensitive to EoS and phase transition

(the change of \( v_1(\eta) \) slope with energy can indicate for a phase transition in some of the models)
Directed flow, $v_1$


- An odd function of rapidity, linear at mid-rapidity
- A sign of the slope for different particle species changes with energy


Mechanism for generating directed flow at lower energies

- Baryon and mesons have different slope $v_1(\eta)$
Directed flow measurements
Reaction plane: directed flow of spectators

Deflection of the spectators in non-central collisions measured by ZDC is used to determine first order reaction plane angle $\Psi_1$ and flow vector $\{X,Y\}$

Neutron Zero Degree calorimeter
(quartz fibers in an absorber)

Spectator deflection:

$$\{X,Y\} = \beta \frac{\sum \{x_i, y_i\} E_i^\alpha}{\sum E_i^\alpha}$$

$E_i$ tower energy; $(x_i, y_i)$ tower center
$\alpha, \beta$ parameters

First order reaction plane angle:

$$\Psi_1 = \tan^{-1}\left(\frac{Y}{X}\right)$$

$\eta > 8.8$, 114 m from interaction point
Event plane and scalar product methods

**EP method**

\[ v_1 = \frac{\langle \cos(\varphi - \Psi_{(A+C) \ell}) \rangle}{\sqrt{2} \langle \cos(\Psi_A - \Psi_C) \rangle} \]

**SP method**

\[ v_{A,C \ell; x,y} = \sqrt{2} \frac{\langle \cos \varphi \cdot X_{A,C} \rangle}{\sqrt{\langle X_A X_C \rangle}} = \sqrt{2} \frac{\langle \sin \varphi \cdot Y_{A,C} \rangle}{\sqrt{\langle Y_A Y_C \rangle}} \]

Resolution correction

- Correlation of deflection coordinates from both sides: sensitivity to directed flow of spectators
- No/weak correlation along orthogonal directions: systematics from detector effects are small
Directed flow measurements

directed flow of produced particles

TPC (Time Projection Chamber) measurements:

✓ tracks in TPC, $|\eta|<0.9$, with transverse momentum $0.15<p_T<10$ Gev/c

✓ number of TPC clusters $\geq 80$ (up to the maximum = 159)

✓ normalized track $\chi^2 \leq 4.0$

✓ longitudinal DCA $\leq 3$ cm; transverse DCA $\leq 3$ cm

Vzero measurements:

✓ 4 rings of plastic scintillators at fixed Z-positions (fixed $\eta$) from both sides from IP

✓ $\phi$-granularity on 8 sectors.

✓ $M_i$ is charged particle multiplicity in a sector $i$

$$V_1^{obs} = \left\langle \frac{\sum M_i \cos(\phi_i - \Psi)}{\sum M_i} \right\rangle$$
LHC predictions vs data

Some transport models (like AMPT) and fluid-dynamic model predicts positive slope of $v_1(\eta)$

Negative slope is observed experimentally
$v_1(\eta)$: comparison with RHIC


- Decrease of $v_1$ with collision energy
- Negative slope of $v_1(\eta)$

- The magnitude of $v_1(\eta)$ much smaller than at top RHIC energy
- The slope decreases, become more flatten
- Weak centrality dependence at mid-rapidity

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☑️ The magnitude of $v_1(\eta)$ much smaller than at top RHIC energy

☑️ The slope decreases, become more flatten

☑️ Weak centrality dependence at mid-rapidity
Longitudinal scaling


- Universal trend when shifted to beam rapidity
- Data follows the longitudinal scaling observed at RHIC
Pt dependence of $v_1$

- Pt dependence is similar to what found at RHIC

- Zero crossing around $p_t = 1.5$ GeV/c

- For peripheral collisions zero crossing point moves toward higher pt
Flow fluctuations:  \[ \sigma^2 = \langle v^2 \rangle - \langle v \rangle^2 \]

- Flow methods are biased by 1) non-flow correlations and 2) flow fluctuations.

- ZDC RP method has a negligible non-flow correlations, but could be sensitive to flow fluctuations (v_1-even).

- A contribution from flow fluctuations is different for a particular method. A measured value for different methods can be approximated as \( \langle v^\alpha \rangle^{1/\alpha} \). For RP method, \( \alpha \) depends on resolution.


In terms of true flow value, v, the EP method:

\[
v_{\text{subEP}} = \frac{\langle v \mathcal{R}(v \sqrt{N/2}) \rangle}{\sqrt{\langle [\mathcal{R}(v \sqrt{N/2})]^2 \rangle}}
\]

The resolution \( R = R(v, N) \) is a function of flow v and multiplicity N.

In \( v_1 \) ZDC EP method resolution \( R \sim v_1 \) (spectators).
Flow fluctuations in $v_1$ measurements

✓ Event-by-event fluctuations in the position of the participating nucleons and the transverse shape of the spectator distribution are connected

$$<v_1^{\text{ZDC EP}}_1> \sim <v_1^{\text{participants}}_1> \times v_1^{\text{spectators}}_1$$

⇒ Mean value:

$$<v_1^{\text{spect}}_1 (>0)> = -<v_1^{\text{spect}}_1 (<0)>$$

Since $v_1$ is an odd function

⇒ E-by-E value:

$$<v_1^{\text{spect}}_1 (>0)> + \sigma \neq -<v_1^{\text{spect}}_1 (>0)> + \sigma$$

⇒ In a EP method:

$$|<v_1_1 (>0)> + \sigma| \neq |<v_1_1 (<0)> - \sigma|$$

Flow fluctuations contribute with opposite sign to the correlation with spectators on the positive and negative rapidity side.
Directed flow with two sub-events

- A difference between two sub-events is consistent with flow fluctuation picture
- Azimuthal correlations with spectators can be sensitive to flow fluctuations at mid-rapidity
The dependence for odd- and even- $v_1$ is the same

The analysis for harmonic decomposition of 2-particle correlations yields the similar shape for even part, but much larger magnitude

First harmonic flow extracted from the two particle correlations at mid-rapidity is susceptible to effects of momentum conservation and other non-flow correlations
Summary

Directed flow of charged particles has been measured at midrapidity, $|\eta| < 0.8$, and forward rapidity, $1.7 < |\eta| < 5.1$, for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at LHC.

- $v_1(\eta)$ has negative slope in contrast to some of the theoretical expectations.
- Magnitude of $v_1$ is smaller than at top RHIC energy.
- $v_1 (\eta-y_{beam})$ is consistent with a picture of longitudinal scaling observed at RHIC.
- $v_1(p_t)$ crosses zero at approximately $p_t = 1.5$ GeV/c, depending on centrality.
- Azimuthal correlations with spectators can be sensitive to flow fluctuations at mid-rapidity.