Anisotropic flow fluctuations of charged and identified hadrons in Pb-Pb collisions with the ALICE detector

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Anisotropic flow and flow fluctuations

- Interactions among constituents transform the initial spatial anisotropy into momentum anisotropy
  \[ E \frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy} \left\{ 1 + \sum_{n=1}^{\infty} 2v_n \cos [n(\phi - \Psi_n)] \right\} \]
- \( v_n \) are sensitive to the evolution of the collision system. (\( \eta/s \), Initial conditions...)
- Initial geometry fluctuations lead to flow fluctuations in the final state
  \[ \langle v_n^k \rangle \neq \langle V_n \rangle^k \]
Anisotropic flow and flow fluctuations of identified particles

- Anisotropic flow of identified particles:
  - Further constraints to initial conditions, particle production mechanisms
  - Probes the freeze-out conditions of the system
- Multi-strange baryons:
  - Expect small hadronic cross-sections.

First measurement of $v_2\{4\}$ (Less sensitive to non-flow) and flow fluctuations of identified hadrons with the ALICE detector
ALICE detector

- Tracks:
  \[ |\eta| < 0.8 \text{ (unidentified)} \]
  \[ |y| < 0.5 \text{ (identified)} \]

- ALICE Pb–Pb at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
  320M events(2015 + 2018 data)

- ITS: Tracking, vertexing, triggering

- TPC: Tracking, PID

- TOF: PID

- V0: Triggering, multiplicity estimation

- Identification of \( \pi^\pm, K^\pm, p(\bar{p}) \):
  - Utilising combined TPC & TOF detectors
  - Track-by-track basis with purity > 80%

Multi-particle cumulant method

- 2- & multi-particle cumulants are obtained using Generic Framework
- The 2- & 4-particle cumulant are given by
  \[ c_n\{2\} = \ll 2 \gg \]
  \[ d_n\{2\} = \ll 2' \gg \]
  \[ c_n\{4\} = \ll 4 \gg -2 \cdot \ll 2 \gg^2 \]
  \[ d_n\{4\} = \ll 4' \gg -2 \cdot \ll 2' \gg \ll 2 \gg \]
- Estimates of differential flow \( v_n \) are denoted as
  \[ v_n\{2\}(p_T) = \frac{d_n\{2\}(p_T)}{\sqrt{c_n\{2\}}} \]
  \[ v_n\{4\}(p_T) = -\frac{d_n\{4\}(p_T)}{(-c_n\{4\})^{3/4}} \]
- Multi-particle cumulant effectively suppress non-flow effect
- \( \eta \) gap suppress short-range correlations
- For reconstructed particles:
  \[ \langle \langle n' \rangle \rangle_{Tot}(m_{inv}) = \]
  \[ \langle \langle n' \rangle \rangle_{Sig} \frac{N_{Sig}(m_{inv})}{N_{Tot}(m_{inv})} + \langle \langle n' \rangle \rangle_{BG} \frac{N_{BG}(m_{inv})}{N_{Tot}(m_{inv})} \]
$p_T$-differential $v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$

- Plethora of charged particles $v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$ measurements in ALICE
- $v_2\{2\}$ larger than $v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$: fluctuations and non-flow
$p_T$-differential $v_2$ PDFs

- Deviation of $v_2\{4\}/v_2\{6\}$ and $v_2\{4\}/v_2\{8\}$ from unity at low $p_T \rightarrow $ Bessel-Gaussian parametrisation of $v_n$ p.d.f. is not valid
- Non-trivial evolution with $p_T$
$p_T$-differential $v_2$ PDFs

- Different moments (Skewness $\gamma_1$ and Kurtosis $\gamma_2$) of the distribution from $v_2\{m\}$ were calculated
  
  \[ \gamma_1 \approx -\frac{2^{3/2}}{2} \frac{v_2\{4\}^3 - v_2\{6\}^3}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}} \]

  \[ \gamma_2 \approx -\frac{3}{2} \frac{v_2\{4\}^4 - 12v_2\{6\}^4 + 16v_2\{8\}^4}{(v_2\{2\}^2 - v_2\{4\}^2)^2} \]

- Dependence of the $v_n$ p.d.f. on $p_T$ is not constant

- Higher $p_T$ ($>3$ GeV/$c$): $\gamma_1$ and $\gamma_2$ are consistent with 0

\[ \text{ALICE Preliminary} \]

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

\[ \text{Pb-Pb, V0M 30-40\%} \]

(ALI-PREL-327438)
$v_2\{4\}$ of identified particles

- First measurement of $v_2\{4\}$ of identified hadrons
- Qualitatively similar behaviour as of $v_2\{2\}$ measurements
  - Clear mass ordering at low $p_T$ and baryon/meson grouping at intermediate $p_T$. 
$n_q$ scaling test for $v_2\{4\}$ of identified particles & hydro calculations

- Both $v_2$ and $p_T$ are scaled by the number of constituent quarks ($n_q$)
- The various hadron species approximately follow a common trend at intermediate $p_T$ (About 20% deviation)
- Hydro calculations can describe $v_2\{4\}$ of $\pi$, $K$, $p$ well
\( v_3\{4\} \) of identified particles

- \( v_3\{4\} \) of identified hadrons has been measured in a wider centrality interval
- Qualitatively similar behaviour as of \( v_3\{2\} \) measurements
  Clear mass ordering at low \( p_T \) and baryon/meson grouping at intermediate \( p_T \)
Flow and flow fluctuation

- Measurements of 2- & 4-particle cumulant are used to study flow and flow fluctuations (if non-flow is negligible in 2-PC)
  [S.A. Voloshin et al. PLB 659 (2008) 537]

\[
v_n\{2\}^2 = (v_n)^2 + \sigma_{v_n}^2
\]

\[
v_n\{4\}^2 \approx (v_n)^2 - \sigma_{v_n}^2
\]

\[
\langle v_n \rangle \approx ((v_n\{2\}^2 + v_n\{4\}^2)/2)^{1/2}
\]

\[
\sigma_{v_n} \approx ((v_n\{2\}^2 - v_n\{4\}^2)/2)^{1/2}
\]

- Non-flow effect of 2-particle cumulant was suppressed by $\eta$ gap
- $\langle v_n \rangle$ is the anisotropic flow from the symmetry plane and $\sigma_{v_n}$ is the corresponding anisotropic flow fluctuations

- Obvious centrality dependence of $\langle v_2 \rangle$ and $\sigma_{v_2}$ for $\Xi$
Relative flow fluctuations

- Relative $v_n$ fluctuations

$$F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$$

- First measurement of relative flow fluctuations for identified hadrons
- No definite particle species dependence
Relative flow fluctuations of identified particles compared with hydro calculations

- Hydro can describe $F(v_2)$ of $\pi$, K, p well in 30-40%
- Hydro calculations with AMPT initial state describe a $F(v_2)$ distribution with obvious particle species dependence at low $p_T$
Summary

- $p_T$-differential measurements of charged particles flow coefficients using 6- and 8-particle cumulants are done for the first time in ALICE.
- $v_2$ distribution is not described well by the Bessel-Gaussian distribution.
- Non-trivial evolution with $p_T$.
- The first measurement of $v_2\{4\}$ and flow fluctuations of identified hadrons.
- No definite particle species dependence observed for relative flow fluctuations of identified particles.
Back up
$p_T$-differential $v_3\{2, 4\}$ and $v_4\{2\}$
Correlation between soft and hard $v_2 \{ m \}$

$|c| < 0.6 \text{ GeV}/T_p (0.5 < 2v_0 < 0.15) \text{ GeV}/T_p (12 < 2v_0 < 14)$

ALICE Preliminary

$\sqrt{s_{NN}} = 5.02 \text{ TeV}$

$\eta_{\Delta}$

$Pb-Pb, |\Delta\eta| > 1$
$p_T$-differential $\gamma_1$ and $\gamma_2$
$v_2\{4\}$ of identified particles
\[ v_2\{4\} / n_q - p_T / n_q \]
$$\frac{v_2\{4\}}{n_q - KE_T / n_q}$$
$v_2\{4\}$ of identified particles compared with hydro calculations using AMPT-IC
$\nu_2(4)$ of identified particles compared with hydro calculations using TRENToIC.
$F(v_2)$ of identified particles compare with hydro calculations using AMPT-IC
$F(v_2)$ of identified particles compare with hydro calculations using TRENTo-IC
Thank you