Anisotropic flow of identified particles in Pb-Pb collisions at 2.76 TeV

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Motivation

Anisotropic flow of identified particles is sensitive to the partonic degrees of freedom at the early times of a heavy-ion collision; studied vs. transverse momentum allows to quantify:

• rate of hydrodynamic radial expansion (mass dependence of $v_n$ vs. $p_T$)
• properties of the deconfined phase (e.g. viscosity)
• details of hadronization mechanism (e.g. coalescence)

Fourier expansion

$$\frac{dN}{d\phi} \propto 1 + 2v_1 \cos[\phi - \Psi_1] + 2v_2 \cos[2(\phi - \Psi_2)] + 2v_3 \cos[3(\phi - \Psi_3)] + ...$$

Anisotropic flow coefficients covered in this talk
Outline

In this talk we present anisotropic flow of \( \pi, K, p, \Lambda, \Xi, \Omega \) and \( \phi \)-meson and investigate the properties of \( v_2 \) and \( v_3 \) vs. transverse momentum:

- particle mass dependence
- quark (light/strange) content
- comparison with hydrodynamic model calculations
- comparison with measurements at RHIC
- \( v_2/v_3 \) scaling properties with number of quarks and transverse kinetic energy.
- Does \( v_3 \) (originating from fluctuations) scale similar to \( v_2 \)?
Analysis details

**VZERO** detector
Two forward scintillator arrays
(-3.7 < \( \eta \) < -1.7, 2.8 < \( \eta \) < 5.1):
centrality / event plane

**Inner Tracking System** (ITS) and **Time Projection Chambers** (TPC):
tracking / event plane

**Time Of Flight** (TOF) and TPC: particle identification

**DATA sample:**
- Pb-Pb at \( \sqrt{s_{NN}} = 2.76 \) TeV
- 2010 data
- \( \sim 10 \)M events

Acceptance: \( |\eta| < 0.8 \)
\[ \pi, K \text{ and } p/\bar{p} \text{ identification} \]

Particle identification with TOF & TPC:
- asymmetric $\beta$-cut to select a high purity sample of $\pi$, $K$ and $p$.
- $2\sigma$ cut in the TPC $dE/dx$.
- $p_T$ range (in GeV/c):
  - $\pi \to 0.3 < p_T < 3.5$
  - $K \to 0.4 < p_T < 2.5$
  - $p \to 0.5 < p_T < 4.0$
- purity: > 90%

Identification at high $p_T$ with TPC:
- purity cut on the TPC $dE/dx$ signal:
- $p_T$ range (in GeV/c):
  - $\pi$ and $p \to 3 < p_T < 16$
  - purity: > 90% for pions, > 80% for protons
**K^0_s, Λ, Ξ, Ω and φ reconstruction**

\[ K^0_s \rightarrow \pi \pi \]
\[ \Lambda(\bar{\Lambda}) \rightarrow p(\bar{p})\pi \]
\[ \Xi^\pm \rightarrow \Lambda \pi^\pm \]
\[ \Omega^\pm \rightarrow \Lambda K^\pm \]
\[ \phi \rightarrow K^+K^- \]

Details on \( v_2 \) of \( K^0_s, \Lambda, \Xi \) and \( \Omega \):
See poster #147 by C. Perez Lara

Details on \( \phi \)-meson \( v_2 \):
See poster #414 by Y. Zhou
Elliptic flow of identified particles
Elliptic flow of $\pi$, K and $p$

- Mass ordering observed for different species. $p_T$ value at which $v_2$ is the same for all species is higher for heavier particle (in the region $p_T < 2$-3 GeV/c)
- Mass dependence persists up to high transverse momenta
Elliptic flow of $K^0_s$ and $\Lambda$

Mass ordering is similar to $v_2$ of charged kaons and protons
Elliptic flow of $\Xi$ and $\Omega$

$v_2$ of heavier particles ($\Xi$ and $\Omega$) are shifted more to higher $p_T$. 

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• at low $p_T$ (where flow is affected by radial boost): $\phi$-meson $v_2$ is similar to $v_2$ of (anti-)protons which has a similar mass
• at high $p_T$ (where coalescence expected to be applicable) $\phi$-meson $v_2$ is similar to $v_2$ of pions (light quark flavour mesons)
Overview of $v_2$ of all measured species

- $v_2$ is measured for a number of particles with light and strange quark content: $\pi, K, p/\bar{p}, K^0_s, \Lambda, \Xi, \Omega$ and $\phi$
- Evident mass hierarchy at low and high $p_T$ which changes with the collision centrality
- For $v_2$ of particles with heavy quark content see:
  - D-meson: talk #460 by D. Caffarri
  - Poster #413 by G. Luparello
  - J/$\Psi$: talk #473 by H. Yang
  - Heavy flavour electrons: talk #470 by S. Shingo
  - Poster #410 by T. Raascanu and Poster #416 by D. Moreira de Godoy
Comparison with hydrodynamic model calculations
Viscous hydrodynamic model calculations reproduce the main features of $v_2$ at low transverse momentum:
• mass dependence is better modelled for peripheral collisions
• for central collisions overestimate proton flow
• Adding hadronic rescattering phase improves the agreement with data Heinz, Shen, Song, AIP Conf. Proc. 1441, 766 (2012)
$\Xi$ and $\Omega$ flow vs. hydro

Hydrodynamic model calculations reproduce larger boost towards higher $p_T$ for $\Xi$ and $\Omega$ (Heinz, Shen, Song, AIP Conf. Proc. 1441, 766 (2012); PRC84 044903)
Comparison with RHIC data
$v_2$ of $\pi$, $K$, $p$ at LHC vs. RHIC

- $v_2$ measured at the LHC is slightly above the RHIC $v_2$ for pions and kaons
- $v_2$ of (anti-)protons reflects effect of larger radial flow at LHC
Similarly, the $\phi$ meson $v_2$ is compatible with larger radial flow at LHC
Elliptic flow scaling properties
• $v_2$ measured in the $p_T$ region of 3-6 GeV/c can be used to test the model of the hadron production via quark coalescence
• $v_2/n_q$ vs. $p_T/n_q$ ($n_q$ is the number of quarks per meson/baryon) shows that if such scaling exists it is only approximate (holds within 20%)
NCQ scaling of $v_2$ vs. transverse kinetic energy

For low $p_T$: $v_2/n_q$ together with KE$_T$ scaling is violated at LHC
For KE$_T$/n$_q$ > 1 GeV/c antiproton’s $v_2$ is lower than that of pions
$v_2/n_q$ and KE$_T$ scaling for all species

NCQ scaling maybe violated also for heavier particles, including the $\phi$-meson
Identified particle triangular flow
• $v_3$ (which originates solely from flow fluctuations) exhibits similar particle mass dependence as that of $v_2$

• The value of $p_T$ at which $v_3$ of all species cross looks similar to that for $v_2$
Elliptic and triangular flow at high transverse momentum

• up to $p_T \sim 8 \text{ GeV/c}$, proton $v_2$ and $v_3$ is larger than that of pion
• pion/proton $v_2$ at high transverse momenta ($p_T > 10 \text{ GeV/c}$) is significant and non-zero, while within experimental uncertainties $v_3$ is consistent with zero


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Summary

Elliptic flow of $\pi$, $K$, $p$, $\Lambda$, $\Xi$, $\Omega$ and $\phi$ is measured vs. transverse momentum for different collision centrality classes for Pb-Pb collision at 2.76 TeV:

- $p_T < 3$ GeV/$c$: observed mass dependence is reproduced by the hydrodynamic model calculations (VISH2+1 CGC, VISHNU)
- The larger mass splitting of $v_2$ to higher $p_T$ observed by ALICE is consistent with stronger radial flow at the LHC
- $KE_T$ scaling does not hold at the LHC
- $p_T \sim 3$-6 GeV/$c$: constituent number of quark scaling holds only approximately (within 20%) 
- $p_T \sim 6$-8 GeV/$c$: mass dependence persist up to high transverse momenta with proton flow being larger than that of pion up to $p_T \sim 8$ GeV/$c$
- $v_3$ of $\pi$, $K$, and $p/\bar{p}$ has a similar mass dependence and crossing point as that of $v_2$
Backup
NCQ scaling of $v_3$ works better than for $v_2$ but it is still only approximate.