Elliptic flow of identified particles in Pb-Pb collisions at the LHC

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- Why elliptic flow?
- ALICE
  - Particle identification
- Flow analysis methods
- Results
- Summary
Why elliptic flow?

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

\[
v_n = \langle \cos \left( n \left( \varphi - \Psi_n \right) \right) \rangle
\]

- Elliptic flow ($v_2$) is sensitive to the system evolution
  - Constrains the initial conditions, deconfined phase, particle production mechanisms
- Identified particle $v_2$ allows for precision measurements
  - Adds further constraints to initial conditions, deconfined phase, particle production mechanisms
  - Probes the freeze-out conditions of the system (temperature, radial flow, ...)
  - Checks the number of constituent quarks (NCQ) scaling

A Large Ion Collider Experiment

- Inner Tracking System (ITS)
  - Tracking, triggering and vertex determination
- Time Projection Chamber (TPC)
  - Tracking and particle identification based on specific energy loss
- Time-of-Flight (TOF)
  - Particle identification based on the arrival time
- V0-A (2.8<\eta<5.1) and V0-C (-3.7<\eta<-1.7)
  - Triggering and centrality determination

Data sample:
- Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV
  - ~15M events analyzed
- Tracks used:
  - -0.8 < \eta < 0.8 (\pi^\pm, K^\pm, p, \phi)
  - -0.5 < y < 0.5 (K_s^0, \Lambda, \Xi, \Omega)
  - 0.2 < p_T < 6 \text{ GeV}/c
- Do not differentiate between particle and antiparticle
Particle identification

- $\pi^\pm$, $K^\pm$, $p$ identified using TPC and TOF
  \[ N_{\sigma,PID}^2 = N_{\sigma,TPC}^2 + N_{\sigma,TOF}^2 \]
  \[ N_{\sigma,PID} < 3 \]
- Topological reconstruction for strange and multi-strange particles
Flow analysis methods

- $v_2$ of $\pi^\pm$, $K^\pm$, $p$ is directly measured using the scalar product method
  - Hits measured by V0-A ($2.8<\eta<5.1$) and V0-C ($-3.7<\eta<-1.7$) detectors are used as reference particles (RPs)
    - Large $\eta$ gap between particles of interest and RPs to suppress non-flow

- $v_2$ of $K_s^0$, $\Lambda$, $\phi$, $\Xi$, $\Omega$ is determined using the $v_2$ vs invariant mass method:
  $v_2^{\text{Tot}}(m_{\text{inv}}) = v_2^{\text{Sgn}} \frac{N^{\text{Sgn}}}{N^{\text{Tot}}(m_{\text{inv}})} + v_2^{\text{Bg}} \frac{N^{\text{Bg}}}{N^{\text{Tot}}(m_{\text{inv}})}$
  - The yields $N^{\text{Sgn}}$ and $N^{\text{Bg}}$ are extracted from fits of the invariant mass distributions
  - The $v_2^{\text{Tot}}(m_{\text{inv}})$ is measured using the scalar product method

\[
v_2 = \sqrt{\frac{\langle \bar{u} \cdot \mathbf{Q}_A^* \rangle \langle \bar{u} \cdot \mathbf{Q}_C^* \rangle}{\langle \mathbf{Q}_A \cdot \mathbf{Q}_C^* \rangle}}
\]
Identified particle $v_2$

ALICE, arXiv:submit/0981508

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<td>$v_2$ $</td>
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<td>$v_2$ $</td>
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ALICE

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

$|\eta| < 0.8$

and $|y| < 0.5$

Particle species

- $\pi^\pm$
- $K^\pm$
- $K^0_s$
- $p+\bar{p}$
- $\phi$
- $\Lambda+\bar{\Lambda}$
- $\Xi^-+\Xi^+$
- $\Omega^-+\bar{\Omega}^+$
Identified particle $v_2$

- Small difference between $v_2$ for $K^\pm$ and $K_s^0$
  - Physics mechanism/detector effect responsible not understood yet
  - $v_2$ for $K^\pm$ and $K_s^0$ averaged for $p_T<4.0$ GeV/$c$ in the following slides
- For $p_T<2$ GeV/$c$: observe mass ordering indicative of radial flow
- For $p_T\sim2-3.5$ GeV/$c$: crossing between $v_2$ of $p$ and $\pi^\pm$
- For $p_T>3$ GeV/$c$: particles tend to group into mesons and baryons
  - $v_2$ of $\phi$ follows baryons for central collisions and shift progressively to mesons for peripheral collisions
Comparison with hydrodynamical calculations ($\pi^\pm$, p, $\Lambda$)

- Hydrodynamical calculations (MC-KLN, $\eta/s=0.16$) coupled to a hadronic cascade model (VISHNU) reproduce the main features of $v_2$ for $p_T<2$ GeV/c
  - Underestimates the $v_2$ for $\pi^\pm$
  - Underpredicts the $v_2$ for p
  - Overestimates the $v_2$ for $\Lambda$
  - Mass ordering is broken in the model

VISHNU: PRC 89, 034919 (2014)
Comparison with hydrodynamical calculations ($K$, $\phi$, $\Xi$)

- Hydrodynamical calculations (MC-KLN, $\eta/s=0.16$) coupled to a hadronic cascade model (VISHNU) reproduce the main features of $v_2$ for $p_T<2$ GeV/c
  - Describes fairly well the $v_2$ for $K$
  - Overestimates the $v_2$ for $\Xi$
  - Overpredicts the $v_2$ for $\phi$
    - Mass ordering is broken in the model

VISHNU: PRC 89, 034919 (2014)
$p_T/n_q$ scaling?

- For $p_T/n_q > 1$-1.5 GeV/c: particles tend to group according to their type
  - $\phi$ does not follow the band of mesons for central collisions
- For $p_T/n_q > 1$ GeV/c: NCQ scaling is only approximate
$p_T/n_q$ scaling?

- For $p_T/n_q > 1$ GeV/c: NCQ scaling deviations at the order of ±20%
  - Similar magnitude for all centrality classes
$KE_T/n_q$ scaling?

$$KE_T = m_T - m_0 \quad m_T = \sqrt{p_T^2 + m_0^2}$$

- For $KE_T/n_q<0.6-0.8$ GeV/$c^2$: significant deviations from NCQ scaling are seen in data
- For $KE_T/n_q>0.8$ GeV/$c^2$: NCQ scaling, if any, is only approximate
$KE_T/n_q$ scaling?

\[ KE_T = m_T - m_0 \quad m_T = \sqrt{p_T^2 + m_0^2} \]

- For $KE_T/n_q < 0.6$-0.8 GeV/$c^2$: NCQ scaling is broken at the LHC
- For $KE_T/n_q > 0.8$ GeV/$c^2$: NCQ scaling deviations at the level of ±20%
  - Similar magnitude for all centrality classes
“NCQ Scaling” from RHIC to LHC

- Deviations at intermediate $p_T$ are qualitatively similar at LHC and RHIC
  - Evolution is different for $\pi$ and $K$
Summary

- $v_2$ for $\pi^\pm$, $K^\pm$, $p$, $K_s^0$, $\Lambda$, $\phi$, $\Xi$, $\Omega$ is measured in Pb-Pb collisions using the ALICE detector
  - Observe mass ordering for $p_T<2$ GeV/c
  - Crossing between $v_2$ of $p$ and $\pi$ for $p_T\sim 2-3.5$ GeV/c
  - Particles tend to group into mesons and baryons for $p_T>3$ GeV/c
    - $v_2$ of $\phi$ follows baryons for central collisions and shift to mesons for peripheral collisions
- Hydrodynamical calculations (MC-KLN, $\eta/s=0.16$) coupled to a hadronic cascade model describe qualitatively the measurements
- Observe deviations from NCQ scaling at the level of $\pm 20\%$
Thanks!
Back up
\(v_2\) from RHIC to LHC

- Different methods used → comparison difficult
  - \(v_2\) for \(\pi^\pm\) and K measured at the LHC is above the RHIC results
  - \(v_2\) of p is slightly lower for \(p_T < 2.0\)-2.5 GeV/c, but higher for \(p_T > 2.5\) GeV/c at LHC than at RHIC