Elliptic flow at high transverse momentum in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE experiment

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- Motivation
- Flow and non-flow
- Experimental methods
- The ALICE experiment
  - Unidentified charged particle $v_2$ at high $p_T$
  - PID $v_2$ at high $p_T$
- Summary
Motivation (I)

- $v_2$ at high $p_T$ is sensitive to the path length dependence of jet quenching
  - Constrain the mechanism responsible for energy loss
  - Functional form of energy loss: $\Delta E = f(E; T, \alpha, L)$
    - $v_2 + R_{AA} \rightarrow R_{AA}(\phi)$
- Coalescence ($2 < p_T < 6$ GeV/c) $\rightarrow v_2$ measured above $p_T = 6$ GeV/c


Motivation (II)

- PID $v_2$ at high $p_T$ determines the regime where the coalescence mechanism stops being important

P. Sorensen, arXiv:0905.0174
Flow and non-flow

- Particle azimuthal distribution measured with respect to the reaction plane is not isotropic (S. Voloshin and Y. Zhang):

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

\[ v_n = \langle \cos(n(\varphi_i - \Psi_{RP})) \rangle \]

- \( v_n \) quantify the event anisotropy
  - \( v_2 \) elliptic flow
  - \( \Psi_{RP} \) can be estimated from particle azimuthal distribution

- Two problems:
  - Non-flow (other sources of azimuthal correlations) quantified by \( \delta_n \):
    \[ \langle \cos(n(\varphi_i - \varphi_j)) \rangle = \langle v_n^2 \rangle + \delta_n \]
  - Flow fluctuations:
    \[ \langle v_n^2 \rangle = \langle v_n \rangle^2 + \sigma_{vn}^2 \]
Experimental methods

- Event plane (EP) method:
  - Calculate the flow vectors: $Q_{n,x} = \sum_i w_i \cos(n \varphi_i)$ \quad $Q_{n,y} = \sum_i w_i \sin(n \varphi_i)$
  - Determine the event plane angle: $\Psi_n = \text{atan2}(Q_{n,y}, Q_{n,x})/n$
  - Obtain the observed flow: $v_{n,\text{obs}} = \langle \cos(n(\varphi_i - \Psi_n)) \rangle$
  - The flow coefficients are given by: $v_n = v_{n,\text{obs}} / R_n$
    - $R_n$ is the event plane resolution: $R_n = \langle \cos(n(\Psi_n - \Psi_{RP})) \rangle$

- Cumulants:
  - 2- and 4-particle azimuthal correlations for an event:
    $\langle 2 \rangle \equiv \langle \cos(n(\varphi_i - \varphi_j)) \rangle, \varphi_i \neq \varphi_j$
    $\langle 4 \rangle \equiv \langle \cos(n(\varphi_i + \varphi_j - \varphi_k - \varphi_l)) \rangle, \varphi_i \neq \varphi_j \neq \varphi_k \neq \varphi_l$
  - Averaging over all events, the 2\textsuperscript{nd} and 4\textsuperscript{th} order cumulants are given:
    $c_2[n] = \langle \langle 2 \rangle \rangle = v_{n,\text{obs}}^2 + \delta_n$
    $c_4[n] = \langle \langle 4 \rangle \rangle - 2 \langle \langle 2 \rangle \rangle^2 = -v_{n,\text{obs}}^4$
A Large Ion Collider Experiment

Description of the experimental setup → Jurgen Schukraft's talk

Analysis → TPC tracks
\[ p_T > 0.2 \text{ GeV/c} \]
\[ |\eta| < 0.8 \]

Centrality selection: V0 amplitude as an estimator → A. Toia's talk
Suppressing non-flow

- By introducing an $\eta$ gap ($|\Delta\eta| > 0.4$)
  - Correlate particles from (-0.8, -0.2) with particles from (0.2, 0.8) (and vice versa)
  - Event plane resolution is calculated from the two $\eta$ sub-events (red points), while for the full event (black points) random sub-events are used
  - Larger $\eta$ gap using $V0 \rightarrow B$. Chang's poster
- Determining $\Psi_{RP}$ using ZDC
- Using multiparticle correlations ($4^{th}$ order cumulant)
Comparison of methods

- Non-flow contributions significant at high $p_T$
  - Addressed in multiple ways: $v_2$\{4\}, $v_2$\{ZDC\}, $v_2$\{EP V0\}, $v_2$\{EP TPC, $|\Delta\eta|>0.4$\}, $v_2$\{SP, $|\Delta\eta|>0.4$\}, $v_2$\{SP\} and $v_2$\{EP TPC\}
- Left: gray band $\rightarrow$ systematic uncertainty for $|\Delta\eta|>0.4$ methods
- Magnitude of the $v_2$ similar with what is reported by STAR
- Correction factor estimated using $\langle u*Q \rangle$ method in pp

\[
v_2 = \frac{\langle u*Q \rangle_{AA}}{M \langle v_2 \rangle} \]
\[
\langle u*Q \rangle_{corr} = \langle u*Q \rangle_{AA} - \langle u*Q \rangle_{pp}
\]
\[
v_2^{corr} = \frac{\langle u*Q \rangle_{corr}}{M \langle v_2 \rangle} = v_2 \frac{\langle u*Q \rangle_{pp}}{M \langle v_2 \rangle}
\]

- Red and green lines in the left figure
- $v_2$\{SP\} corrected with green line, while $v_2$\{SP, $|\Delta\eta| > 0.4$\} corrected with red line (see next slide)
\( v_2\{\text{AA-pp}\} \)

corrected using \(<u^*Q>\) method in pp
$v_2$ charged particles

- Left plot: dashed lines $\rightarrow$ systematic uncertainties
  - The estimated non-flow correction from pp is included in the systematic error
- $v_2$ at high $p_T$ ($p_T > 8$ GeV/c) is finite and positive
  - Reaches a constant value dependent of centrality
  - Increasing with centrality

\[ R_{AA}(\varphi) \]

- \( v_2 \{ \text{SP, } |\Delta\eta|>0.4, \text{AA-pp} \} + R_{AA} \rightarrow R_{AA}(\varphi) \):
  \[
  R_{AA}(\varphi) = R_{AA}(1 + 2v_2 \cos(2\varphi))
  \]
  \( \varphi = 0 \rightarrow \text{In plane} \)
  \( \varphi = \pi/2 \rightarrow \text{Out of plane} \)

- Systematic uncertainty (gray band): \( v_2 \) and \( R_{AA} \) systematics added in quadrature
PID@high $p_T$

- PID based on the ionization energy loss in the TPC
  - Calculate $\Delta_{\pi} = \frac{dE}{dx} - \langle \frac{dE}{dx} \rangle_{\pi}$
- Select small ranges where the contamination is small:
  - Pions: contamination $< 1 \%$
  - Protons: contamination $< 15 \%$
PID $v_2^{EP}$ TPC, $|\Delta \eta| > 0.4$

- Correcting for non-flow using data from centrality bin 70-80%:

  \[ v_{2,cent}^{corr} = v_{2,cent} - v_{2,70-80\%} \frac{M_{70-80\%}}{M_{cent}} \]

  - Correction included in the systematic uncertainty

- Proton $v_2$ higher than pion at intermediate $p_T$

- Pion and proton $v_2$ start to overlap within systematic uncertainties for $p_T > 8$ GeV/c

- Good agreement with PHENIX data
Summary

- Charged particle elliptic flow has been measured up to $p_T = 20$ GeV/c
  - $v_2$ is finite, positive and approximately constant at $p_T > 8$ GeV/c
  - $R_{AA}(\phi)$ might be sensitive to path length dependence
- Identified particle elliptic flow has also been measured up to $p_T = 20$ GeV/c
  - Indication that jet quenching becomes dominant for $p_T > 8$ GeV/c
- Need feedback from the theory community