Elliptic Flow of D Mesons in Pb-Pb Collisions

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Journal Club on heavy-ion collisions

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ALICE papers discussed

- **D meson elliptic flow in non-central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV**
  PRL 111, 102301 (2013)
  - elliptic flow $v_2$ of $D^0$, $D^+$, $D^{*+}$ in 30-50% centrality

- **Azimuthal anisotropy of D meson production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV**
  - $v_2$ of $D^0$, $D^+$, $D^{*+}$ in 3 centrality classes in 0-50%
  - 3 different methods to determine $v_2$
  - $R_{AA}$ with respect to event plane
What is Azimuthal Anisotropy?

coordinate basis in momentum space: \((p_T, y, \phi)\)

ultrarelativistic heavy-ion collisions:
collision geometry not symmetric in \(\phi\)
\(\rightarrow\) initial spatial azimuthal anisotropy
\(\rightarrow\) particle production \(dN/d\phi\) can be anisotropic depending on the effect of the quark gluon plasma (QGP)
What is Flow?

- thermalized QGP can be described by hydrodynamics
- Euler equation: collective dynamics driven by pressure gradients
- expansion of the fireball
- flow is affected by azimuthal anisotropy
  → different pressure gradients in different directions

Initial spatial anisotropy

Momentum-space anisotropy
Characterizing Anisotropy

dN/dφ - 2\pi-periodic function in φ
→ expand in Fourier series

\[
\frac{dN}{dφ} = \frac{N_0}{2\pi} \left[ 1 + 2 \sum_{n=0}^{\infty} v_n \cos [n(φ - Ψ_n)] \right]
\]

Fourier coefficients:

\[
v_n = \frac{2\pi}{dN} \cos [n(φ - Ψ_n)] dφ = \langle \cos [n(φ - Ψ_n)] \rangle
\]

shape of participant zone (overlap of the nuclei)
Centrality Classes

- more central collision $\rightarrow$ higher multiplicity
- take amplitude in VZERO detectors (scintillators) as a measure for multiplicity
- cluster into percentiles = centrality classes
Outline

- Introduction
  - heavy quarks in the QGP
  - interest in measuring charm flow
- Analysis
  - reconstruction of D mesons in ALICE
  - ALICE detector
  - determination of $v_2$
- Results
- Conclusion
Heavy Quarks in the QGP

- heavy quarks: charm \( \sim 1.5 \) GeV, bottom \( \sim 4.5 \) GeV, [top \( \sim 173 \) GeV]

- \( m_c, m_b \gg \Lambda_{\text{QCD}} \)
  - heavy quarks produced in early pQCD stage

- masses generated mainly by Higgs field
  - \( \rightarrow \) remain heavy when chiral symmetry is restored

- \( m_c, m_b \gg T_{\text{QCD}} \)
  - \( \rightarrow \) no thermal production in medium

- no annihilation

- total charm/beauty is conserved in the medium

- heavy quark experiences full evolution of the system

heavy quark = unique probe of QGP medium properties
Charm $v_2$

- two contributing mechanisms:
  - collective expansion (low $p_T$)
  - path-length dependence of in-medium energy loss (high $p_T$)
- does charm participate in the collective expansion?
- how does charm interact in the QGP?
- strong interplay between experiment and theory
## Reconstruction of D Mesons in ALICE

<table>
<thead>
<tr>
<th>meson</th>
<th>M (GeV/c²)</th>
<th>cτ (µm)</th>
<th>decay channel</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D⁰ (cubar)</td>
<td>1865</td>
<td>123</td>
<td>K⁻π⁺</td>
<td>3.9</td>
</tr>
<tr>
<td>D⁺ (cdbar)</td>
<td>1870</td>
<td>312</td>
<td>K⁻π⁺π⁺</td>
<td>9.1</td>
</tr>
<tr>
<td>D∗⁺ (cdbar)</td>
<td>2010</td>
<td>Γ = 83.3 keV</td>
<td>D⁰(K⁻π⁺)π⁺</td>
<td>67.7</td>
</tr>
<tr>
<td>D⁺ (csbar)</td>
<td>1969</td>
<td>150</td>
<td>φ(K⁻K⁺)π⁺</td>
<td>5.5</td>
</tr>
</tbody>
</table>

+ anti-particles

- D mesons decay before they can be detected
- invariant mass analysis in selected decay channels
- downside: large combinatorial background
  - need excellent particle identification (PID)
  - exploit topology of secondary decay vertex
ALICE Detector

**Time Projection Chamber (TPC)**
- tracking of decay products
- particle identification via dE/dx

**Inner Tracking System (ITS)**
- tracking of decay products
- detection of secondary vertices

**VZERO**
- trigger
- centrality classes

**Time of Flight (TOF)**
- particle identification via flight time
Particle Identification

- specific energy loss $\text{d}E/\text{d}x$ in TPC gas
- velocity $\beta$ via time of flight in TOF
- require measured signal to be within $3\sigma$ of the expected signal for each species ($K, \pi$)

![Graph showing dE/dx in TPC and TOF plots for different particles with kaon hypothesis highlighted.](image)
Topological Selection for $D^0$

- decay vertex displaced from primary vertex by a few 100 µm
- most effective topological cuts:
  - pointing angle: $\cos(\theta_{\text{pointing}}) > 0.95$
  - product of impact parameters: $d_0^K \times d_0^\pi < - (200 \, \mu m)^2$

- kinematic range: $|y| < 0.8$, $2 < p_T < 16$ GeV/c
- topological approach limited at ultra-low $p_T$
Reconstruction of the Event Plane

\[ \frac{dN}{d\phi} = \frac{N_0}{2\pi} \left[ 1 + 2 \sum_{n=0}^{\infty} v_n \cos [n(\phi - \Psi_n)] \right] \]

- reconstruct event plane angle \( \psi_2 \) from the distribution of charged particles
- select ‘good’ TPC tracks from event
- exclude candidates for D mesons to remove auto-correlations

\[ \vec{Q} = \left( \frac{\sum_{i=1}^{N} w_i \cos 2\varphi_i}{\sum_{i=1}^{N} w_i \sin 2\varphi_i} \right) \quad \psi_2 = \frac{1}{2} \tan^{-1} \left( \frac{Q_y}{Q_x} \right) \]

- \( N \) - multiplicity of the event
- \( \varphi_i \) - azimuthal angle of particle \( i \)
- \( w_i \) - weight to correct for azimuthal non-uniformity in TPC
Event Plane Method

\[ \frac{dN}{d\phi} = \frac{N_0}{2\pi} \left[ 1 + 2 \sum_{n=0}^{\infty} v_n \cos [n(\phi - \Psi_n)] \right] \]

- divide \( \phi \) into 4 quartiles
- 2 categories: in plane, out of plane
- integrate \( dN/d\phi \) to get the yields \( N_{\text{in-plane}} \) and \( N_{\text{out-of-plane}} \)
- \( v_2 \) can be determined as:

\[ v_2 = \frac{1}{R_2} \frac{\pi N_{\text{in-plane}} - N_{\text{out-of-plane}}}{4 N_{\text{in-plane}} + N_{\text{out-of-plane}}} \]
Invariant Mass Distributions

- invariant mass of daughter particles (e.g. $K\pi$ for $D^0$)
- fitted by second order polynomial (for the background) plus Gaussian (for the signal)
- extract $N_{\text{in-plane}}$ and $N_{\text{out-of-plane}}$ as the integral of the Gaussian
- higher yield in-plane than out-of-plane
- $\rightarrow$ non-negative $v_2$

\[
v_2 = \frac{1}{R_2} \frac{\pi}{4} \frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}
\]
Feed-Down from B

\[ B \rightarrow D + X \]

- Contribution of D mesons from B decays \(-10-20\%\)
- Feed-down enhanced by topological selection
- Want to give result for prompt D only
- \( m_b > m_c \) \( \rightarrow \) \( v_2^{\text{feed-down}} \leq v_2^{\text{prompt}} \)
- Most conservative assumption:
  \( v_2^{\text{feed-down}} = v_2^{\text{prompt}} \) \( \rightarrow \) \( v_2^{\text{prompt}} = v_2^{\text{all}} \)
- Use as an upper limit for systematic uncertainties:
  - Use \( v_2^{\text{feed-down}} = 0 \) \( \rightarrow \) \( v_2^{\text{prompt}} = v_2^{\text{all}} / f^{\text{prompt}} \)
Relevant Systematic Uncertainties

<table>
<thead>
<tr>
<th>Particle v2 analysis</th>
<th>$v_2{\text{EP}}$</th>
<th>$v_2{\text{SP}}$</th>
<th>$v_2{2}$</th>
<th>$v_2{\text{EP}}$</th>
<th>$v_2{\text{SP}}$</th>
<th>$v_2{2}$</th>
<th>$v_2{\text{EP}}$</th>
<th>$v_2{\text{SP}}$</th>
<th>$v_2{2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ and $v_2$ fit stability</td>
<td>9%</td>
<td>10%</td>
<td>8%</td>
<td>25%</td>
<td>8%</td>
<td>17%</td>
<td>30%</td>
<td>14%</td>
<td>11%</td>
</tr>
<tr>
<td>2 or 3 sub-ev. $R_2$</td>
<td>2.3%</td>
<td>-</td>
<td>-</td>
<td>2.3%</td>
<td>-</td>
<td>-</td>
<td>2.3%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$R_2$ centrality dependence</td>
<td>2%</td>
<td>10%</td>
<td>10%</td>
<td>-</td>
<td>10%</td>
<td>10%</td>
<td>-</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Centrality selection</td>
<td>-</td>
<td>10%</td>
<td>10%</td>
<td>-</td>
<td>10%</td>
<td>10%</td>
<td>-</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Total (excl. B feed-down)</td>
<td>9%</td>
<td>14%</td>
<td>13%</td>
<td>25%</td>
<td>13%</td>
<td>20%</td>
<td>30%</td>
<td>17%</td>
<td>15%</td>
</tr>
<tr>
<td>B feed-down</td>
<td>+48% -0%</td>
<td>+26% -0%</td>
<td>+26% -0%</td>
<td>4 &lt; $p_T$ &lt; 6 GeV/c, 30-50%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- signal extraction
  - vary fit range, functional form, binning...
  - bin counting instead of integral
  - fix fit parameters

- feed-down from B
  - as described on previous slide

Journal Club on heavy-ion collisions, 6 June 2014
Results

- **D meson elliptic flow in non-central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV**
  
PRL 111, 102301 (2013)
  
  - elliptic flow $v_2$ of $D^0$, $D^+$, $D^{*+}$ in 30-50% centrality

- **Azimuthal anisotropy of D meson production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV**
  
  
  - $v_2$ of $D^0$, $D^+$, $D^{*+}$ in 3 centrality classes in 0-50%
  - 3 different methods to determine $v_2$
  - $R_{AA}$ with respect to event plane
D meson $v_2$ in 30-50% centrality

- first measurement of D meson $v_2$ in ALICE!
- non-zero $v_2$ for all species
- $v_2$ of different species consistent within uncertainties
Average \( D \) meson \( v_2 \) in 30-50% 

- \( v_2 \) of \( D \) mesons comparable to light flavor
- \( v_2 \) in \( 2<p_T<6 \) GeV/c: \( 0.204 \pm 0.030 \) (stat) \( \pm 0.020 \) (syst) \( ^{+0.092}_{-0} \)
- larger than 0 with 5.7\( \sigma \)!

- average computed using statistical significance as weights
- full propagation of systematic uncertainties
Results

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D_0 Elliptic Flow vs. centrality

- indication for increase of v_2 vs. mid-central collisions
- comparable to charged particles in all centrality bins
Modelling Flow

- e.g. BAMPS model:
- Boltzmann approach to multi-parton scattering
- microscopic partonic transport model
- implemented processes:
  - elastic collisions
  - gluon radiation

\[ q(p_1) \rightarrow q(p_3) \]
\[ q(p_2) \rightarrow q(p_4) \]

\[ g(q) \]

O. Fochler, J. Uphoff, Z. Xu and C. Greiner

\[ 2 \rightarrow 2 \]
\[ 2 \rightarrow 3 \]
Comparison with Models

- many different models exist that predict $v_2$
- with better precision (Run 2) models will be constrained further
Take Home Messages

- D mesons reconstructed via invariant mass analysis using topological selection and particle identification
- D meson elliptic flow $v_2$ measured for the first time in ALICE
- in $2 < p_T < 6$ GeV/c:
  - $v_2 = 0.204 \pm 0.030$ (stat) $\pm 0.020$ (syst) $^{+0.092}_{-0}$
  - $v_2 > 0$ with 5.7$\sigma$ significance
- elliptic flow of D mesons and charged particles consistent within uncertainties
- indication for an increase of $v_2$ from central to mid-central collisions

\[\text{evidence for collective flow of charm quarks}\]

- no model describes all data yet $\rightarrow$ challenge for theory!
Backup
○ stronger suppression in out-of-plane direction where the path length is larger
Elliptic Flow with Different Methods

Prompt $D^0$, $D^0$ $|y|<0.8$

$\nu_2$ (EP TPC)

ALICE $\nu_2$ (SP TPC)

$\nu_2$ (2)

Prompt $D^+$ $|y|<0.8$

$\nu_2$ (EP TPC)

$\nu_2$ (SP TPC)

$\nu_2$ (2)

Prompt $D^{*+}$ $|y|<0.8$

$\nu_2$ (EP TPC)

$\nu_2$ (SP TPC)

$\nu_2$ (2)

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

Centrality 30-50%

Open box: syst. from data

Shaded box: syst. from B feed-down

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