Centrality dependence of $D^0$ elliptic and triangular flow in $Au+Au$ at $\sqrt{s_{NN}} = 200$ GeV at STAR

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For the STAR Collaboration

$D^0$ v2 paper has been submitted - arXiv:1701.06060
Why heavy flavor?

Heavy flavor quarks

- Produced early: experience the entire evolution of the Quark-Gluon Plasma (QGP)
- Harder to thermalize: probe the dynamics of the QGP
- Brownian motion approach: heavy quark spatial diffusion coefficient in the QGP, e.g. $2\pi T D_s$

Elliptic and triangular anisotropy

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

- Light flavor \( v_n \) suggests hydrodynamic behavior of a strongly interacting matter
- Heavy quark \( v_n \) sensitive to the degree of thermalization
- Constrain heavy-quark spatial diffusion coefficient

B. Alver, G. Roland, PRC81 (2010) 054905

STAR PRC72, 014904 (2005)
PHENIX PRL 91,182301 (2003)
STAR detector

Time Of Flight detector
PID \((1/\beta)\)

Time Projection Chamber
Tracking, \(dE/dx\)

\(-1 < \eta < 1, \ 0 \leq \phi < 2\pi\)

Heavy Flavor Tracker
(2014-2016)
HFT (Heavy Flavor Tracker)

Complete topological reconstruction of charm hadrons (e.g. $D^0 \rightarrow K\pi$, $c\tau \sim 120 \mu m$)

- $-1 < \eta < 1$, $0 \leq \phi < 2\pi$

- SSD – Silicon Strip Detector ($r \sim 22cm$)
- IST – Intermediate Silicon Tracker ($r \sim 14cm$)
- PXL – Pixel Detector ($r \sim 2.8 \& 8cm$), 0.5%$X_0$ per layer ($20.7 \mu m \times 20.7 \mu m$)
$D^0(\overline{D^0}) \rightarrow K^{\pm} \pi^{\pm}$  
B.R. 3.9%  
$c\tau \sim 120 \ \mu m$

Topological cuts optimized using TMVA  
(Toolkit for Multivariate Analysis)

<table>
<thead>
<tr>
<th></th>
<th>w/o HFT</th>
<th>w/ HFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>#events(MB) analyzed</td>
<td>1.1 billion</td>
<td>~900 million</td>
</tr>
<tr>
<td>sig. per billion events</td>
<td>13*</td>
<td>220</td>
</tr>
</tbody>
</table>

$L. \text{Adamczyk et al. (STAR), PRL113 142301}$
Event plane method

- Event plane (EP) reconstructed using TPC tracks with acceptance non-uniformity corrected
- Tracks in $\eta$-sub region are used to reconstruct EP to suppress non-flow effects

$$v_n\{\text{EP}\} = v_n^{\text{obs}}\{\text{EP}\} \times \left( \frac{1}{\text{EP Resolution}} \right)$$

$\Delta \eta_{\text{min}} = 0.05$

$D^0$ candidate $\eta$-sub region

$3.0 < p_T < 3.5 \text{ GeV/c}$

$\nu_2^{\text{obs}} = 0.085 \pm 0.010$

A.M. Poskanzer and S.A. Voloshin. PRC 58 (1998) 1671

Liang He, QM2017, Chicago
Two-particle correlation method

\[ V_{2Dh} = \langle \cos(2\phi_D - 2\phi_h) \rangle = v_{2D} \cdot v_{2h} \]

\[ V_{2h} = \langle \cos(2\phi_{h1} - 2\phi_{h2}) \rangle = (v_{2h})^2 \]

\[ V_{2\text{signal}} = \frac{N_{\text{cand}} \cdot v_{2\text{cand}} - N_{\text{bkg}} \cdot v_{2\text{bkg}}}{N_{\text{signal}}} \]

Background estimated from side-band

• Same \( \Delta \eta \) gap as used in EP method
$D^0 v_2$ from two methods

![Graph showing $v_2$ vs. $p_T$ for STAR Au+Au at 200 GeV, 0-80%]

- Good agreement

STAR Au+Au @ 200 GeV, 0-80%
- event plane method
- correlation method (Shifted)
D⁰ v₂ compared to light hadrons

- Clear mass ordering for pₜ < 2 GeV/c
- D⁰ follows other light mesons for pₜ > 2 GeV/c

Non-flow is estimated from D⁰-hadron correlation in p+p collisions
D^0 v_2 follows NCQ scaling

• Suggest that charm quarks flow with the QGP
**D⁰ v₂ compared to models**

**Different models:**
- **SUBATECH**: pQCD + hard thermal loop
  - P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, *Strangeness in quark matter*
- **TAMU**: T-matrix, non-perturbative model with internal energy potential
  - M. He, R. J. Fries, and R. Rapp, *PRC86*, 014903 (2012)
- **Duke**: free constant Dₜ, fit to LHC high p_T R_AA
- **hydro**: A 3D viscous hydrodynamic model
- **PHSD**: Parton-Hadron-String Dynamics, a transport model
  - H. Berrehrah et al., *PRC90* (2014) 051901
- **LBT**: A Linearized Boltzmann Transport model

<table>
<thead>
<tr>
<th>compare with</th>
<th>2πTDₜ</th>
<th>χ²/n.d.f.</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D viscous hydro</td>
<td>-</td>
<td>3.6 / 6</td>
<td>0.73</td>
</tr>
<tr>
<td>LBT</td>
<td>3-6</td>
<td>11.1 / 8</td>
<td>0.19</td>
</tr>
<tr>
<td>PHSD</td>
<td>5-12</td>
<td>8.7 / 7</td>
<td>0.28</td>
</tr>
<tr>
<td>TAMU c quark diff.</td>
<td>2-12</td>
<td>10.0 / 8</td>
<td>0.26</td>
</tr>
<tr>
<td>SUBATECH</td>
<td>2-4</td>
<td>15.2 / 8</td>
<td>0.06</td>
</tr>
<tr>
<td>TAMU no c quark diff.</td>
<td>-</td>
<td>29.5 / 8</td>
<td>2 x 10⁻⁴</td>
</tr>
<tr>
<td>DUKE</td>
<td>7</td>
<td>37.5 / 8</td>
<td>2 x 10⁻⁵</td>
</tr>
</tbody>
</table>
Temperature dependence of $2\pi T D_s$ in models

- Dynamic models describe data well
  - with diffusion coefficient $2\pi T D_s$ of $\sim 2-5$ at $T_c$
  - a temperature dependent range of $\sim 2-12$ at $T_c$ to $2T_c$
First measurement of $D^0 v_3$ at RHIC

$D^0 v_3$ is non-zero ($\chi^2/n.d.f. = 17.5/4$)

$D^0 v_3$ consistent with NCQ scaling within large error bars
**D⁰ v₃ compared to model**

- Need more statistics
- More details see poster by M. Lomnitz (B18)
Summary and outlook

• Large non-zero $D^0 v_2$ and $v_3$: strong collective behavior

• Charm $v_n$ follows NCQ scaling as light hadron $v_n$
  • suggests that charm quarks have gained significant flow through interactions with the QGP

• Models consistent with $D^0 v_2$
  • 3D viscous hydrodynamic model describes data below 4 GeV/c: suggesting charm quarks have achieved thermal equilibrium
  • Dynamic models describe data well with diffusion coefficient $2\pi T D_s$ of ~2-5 at $T_c$, and a temperature dependent range of ~2-12 within $2T_c$

• More data are coming: two billion events recorded in 2016
Backups
**Topological cuts**

\[ D^0(\overline{D^0}) \rightarrow K^\mp \pi^\pm \]

B.R. 3.9% \( c\tau \sim 120 \, \mu m \)

**Topological cuts:**
- decay length
- \( \text{DCA}_{K\pi} \)
- \( \text{DCA}_{V0-to-PV} \)
- \( \text{DCA}_K \)
- \( \text{DCA}_\pi \)

\( \text{DCA} : \) Distance of Closest Approach

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**TMVA (Toolkit for Multivariate Analysis)**

- **Signal**
- **Background**
Non-flow effect

\[ v_{2\text{non-flow}} = \frac{\left\langle \sum_i \cos\left(2\left(\phi_{D^0} - \phi_i\right)\right) \right\rangle}{M\left\langle v_2 \right\rangle} \]

- \( \cos(2(\phi_{D^0}-\phi_i)) \): D\(^0\)-hadron from p+p collisions
- \( p_T > 3 \text{ GeV/c} \): deduced from D\(^*\)-hadron correlations using STAR 2012 data
- \( p_T < 3 \text{ GeV/c} \): PYTHIA simulation
- \( M, \langle v_2 \rangle \): multiplicity and average hadron \( v_2 \) in Au+Au collisions
- Same \( \Delta \eta \) gap is applied in estimating D\(^0\)-hadron correlation and hadron \( v_2 \)
Compared to NPE

- $D^0$ and NPE $v_2$ are consistent

$D^0$ $v_2$ STAR AuAu@200GeV, 0-80%

NPE $v_2$ PHENIX AuAu@200GeV, 0-80%

B meson $v_2$ follows NCQ scaling

B meson $v_2$ is zero
Compared to QM2014

STAR Preliminary

Anisotropy Parameter, $v_2$

STAR Au+Au @ 200 GeV
0-80%

$\rho_T$ (GeV/c)
The escape mechanism: $v_2$ due to anisotropic escape probability

~69% of $v_2$ originates from escape