Studies of Heavy-Flavor Jets Using D\(^0\)-hadron Correlations in Azimuth and Pseudorapidity in Au+Au Collisions at \(\sqrt{s_{_{\text{NN}}}} = 200\) GeV at the STAR Experiment

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Motivation

• Why heavy flavor quarks?
  • Heavy flavor (HF) quarks and hadrons provide unique insight into the QGP because of their early formation time, and their decay outside the medium - sensitive to the evolution of the entire medium.
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  • Correlations allow for the study of the shape and per-trigger yields of jet-like structures.
    • Allows for the analysis of effects of radiative and collisional energy loss.
  • 2D correlations on (Δη,Δφ) allow for separation of jet-like structures and flow-harmonics directly.
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Theory originally predicted HF quarks would lose less energy than LF quarks in a QGP [1-3].
Comparison of the correlations from HF quarks and LF quarks provide insight into this prediction.

Relativistic Heavy Ion Collider (RHIC)

- Located at Brookhaven National Laboratory in Upton, NY (Long Island).
- Various energies and species
  - Au, Cu, U, He-3, deuteron, etc.
  - **Au-Au**: $\sqrt{s_{NN}} = 200 \text{ GeV}$, 62 GeV – 3 GeV.
  - **p-p**: $\sqrt{s} = 200 \text{ GeV}$, $\sqrt{s} = 510 \text{ GeV}$, etc.
- Proton spin studies
- Baseline measurements for heavy-ion collisions
Schematic View of STAR

Time Projection Chamber (TPC)

Heavy Flavor Tracker (HFT)

• TPC acceptance
  • $2\pi$ in azimuth
  • $|\eta| < 1$
  • Reconstructed track $p_T > 0.15$ GeV/c

• HFT acceptance
  • $2\pi$ in azimuth
  • $|\eta| < 1$
  • DCA resolution in both $r\phi$ and $z$ directions $\sim 30 \mu m$ at $p_T \geq 1$ GeV/c
Event and Track Selection

- **Event Selection**
  - Minimum-bias events (~900M) recorded in 2014.
  - Primary vertex $|V_Z| < 6$ cm (HFT acceptance)

- **Track Selection**
  - All tracks must be “HFT” tracks
  - $D^0$ Reconstruction (trigger)
    - Wide $p_T$-bin: 2-10 GeV/c
    - K and $\pi$ ID with TPC dE/dx
  - Associated hadron cuts (associated)
    - $|\eta| < 1.0$, $p_T > 0.15$ GeV/c

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### Topological Cuts

<table>
<thead>
<tr>
<th>Cut Description</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>1) Decay Length $\mu$m &gt;</td>
<td>212</td>
</tr>
<tr>
<td>2) DCA Daughters $\mu$m &lt;</td>
<td>57</td>
</tr>
<tr>
<td>3) DCA $D^0$ and PV $\mu$m &lt;</td>
<td>38</td>
</tr>
<tr>
<td>4) DCA daughter $\pi$ and PV $\mu$m &gt;</td>
<td>86</td>
</tr>
<tr>
<td>5) DCA daughter K and PV $\mu$m &gt;</td>
<td>95</td>
</tr>
</tbody>
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2D Angular Correlations

\[ \Delta \varphi = \varphi_{D^0} - \varphi_{h^\pm} \]

\[ \Delta \eta = \eta_{D^0} - \eta_{h^\pm} \]

Correlation measure:

\[ corr. = \frac{SE - \alpha ME}{\alpha ME} = \frac{SE}{\alpha ME} - 1 \]

Raw distributions are dominated by uncorrelated background and pair acceptance.
D⁰ Invariant Mass Background Subtraction

- The **signal region** contains both real D⁰s and background Kπ pairs.
- Correlations from background Kπ pairs are estimated from **sidebands**.
- These normalized **sideband** correlations are then subtracted from those coming from the **signal region**.
Additional Background from D* Decay

- $D^{*±} \rightarrow D^0 + \pi^{±}$ (BR $\sim 67\%$).
  - Accounts for $\sim 20\%$ of our $D^0$ sample.
  - Happens at predominantly small angles between the $D^0$ and $\pi^{±}$, which means we get an increase of $D^0$-hadron pairs only in the $(\Delta \eta, \Delta \phi) = (0,0)$ bin from the $D^0 + \pi^{±}$ pair.

- $D^0_{p_T} = 2-10 \text{ GeV/c}$

What we want.

What we DON’T want.

D⁰-hadron Correlations in Au+Au $\sqrt{s_{NN}} = 200$ GeV
Symmetrized on ($\Delta \eta, \Delta \phi$), D⁰ $p_T = 2$-10 GeV/c, $h^\pm$ $p_T > 0.15$ GeV/c

• Significant structure is seen on ($\Delta \eta, \Delta \phi$) that evolves with centrality.

PYTHIA pp200 data sample (3M events) for D⁰-Hadron correlations (D⁰ $p_T = 2$-10 GeV/c, Tune: [1,2]).

A Simple Mathematical Model to Fit the Data

- Fitting is done with a simple model with 8 parameters:

\[ A_0 + 2A_Q\{2D\} \cos(2\Delta \phi) + A_{NS}e^{-\frac{1}{2}\frac{\Delta \eta^2}{\sigma_{NS,\Delta \eta}}} e^{-\frac{1}{2}\frac{\Delta \phi^2}{\sigma_{NS,\Delta \phi}}} + A_{AS}e^{\frac{1}{2}\frac{\Delta \eta^2}{\sigma_{AS,\Delta \eta}}} e^{-\frac{1}{2}\frac{(\Delta \phi-\pi)^2}{\sigma_{AS,\Delta \phi}}} \]

+ periodicity for $\Delta \phi$ Gaussian

\[ A_Q\{2D\} = v_2^{h\pm}\{2D\}v_2^{D0}\{2D\} \]

(details in backup)

NS Associated Yield = \[ \frac{n_{h\pm}(cent)}{4\pi} \int \Delta \eta \Delta \phi A_{NS}e^{-\frac{1}{2}\frac{\Delta \eta^2}{\sigma_{NS,\Delta \eta}}} e^{-\frac{1}{2}\frac{\Delta \phi^2}{\sigma_{NS,\Delta \phi}}} \]
Fit Results

D^0 p_T = 2-10 GeV/c, h^±p_T > 0.15 GeV/c

Data

50-80%

20-50%

0-20%

Fit

Residual

nSigma Residuals

STAR preliminary

STAR preliminary

STAR preliminary

STAR preliminary

STAR preliminary

STAR preliminary

STAR preliminary

STAR preliminary

STAR preliminary

STAR preliminary

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$D^0 v_2$ Consistency Check with Published Data

- Extracted $v_2$ of the $D^0$ from this analysis agrees with previous measurement in the overlapping, mid-central bin [5].
- The results (red) on the right-hand plot are from QM2017, when different $p_T$ bins were used. The result from the newer $p_T$ binning is consistent in this mid-central region.
- $v_2^{h\pm}$ extracted from [4].

\[ A_Q\{2D\} = v_2^{h\pm}\{2D\}v_2^0\{2D\} \]

Fit-Parameter Results (for the Near-Side Peak)

- First measurement containing $\Delta\eta$-dependence of $D^0$-hadron correlations.
- Broadening of near-side jet-like peak seen in both $\Delta\eta$ and $\Delta\phi$ from 50-80% to 20-50% in centrality, but stays constant within errors from 20-50% to 0-20%.
- The peripheral centrality bin (50-80%) matches closely with what is seen in PYTHIA (tune parameters from [1,2]).

Near-Side Associated Yield Results

- NS associated yield increases with centrality.
- The trend with centrality is similar to the trends seen in light-flavor correlations at similar mean $p_T$.
- The NS associated yield in PYTHIA (Tune:[1,2]) is consistent with the yield in 50-80% Au+Au.

Conclusions

• First measurement of 2D D⁰-hadron angular correlations in heavy-ion collisions.
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• Comparison of near-side widths and yields to light-flavor correlations at similar trigger mean-\(p_T\) indicate similar behavior of correlations with a light-flavor or heavy-flavor (charm) trigger.
Conclusions

• First measurement of 2D D⁰-hadron angular correlations in heavy-ion collisions.
• Comparison of near-side widths and yields to light-flavor correlations at similar trigger mean-\(p_T\) indicate similar behavior of correlations with a light-flavor or heavy-flavor (charm) trigger.
• Near-side widths and yields in the 50-80% centrality agree with PYTHIA, indicating minimal effects of the medium on the jet-like peak, coincident with a non-zero value of \(v_2\).
Thank you!
Backup
D^0 Reconstruction with the Heavy Flavor Tracker (HFT)

- Reconstructed via the hadronic decay channel
  \( D^0 (\text{and} \ D^\ast) \rightarrow K + \pi \); \( \text{BR} \sim 4\% \).

- Challenging due to high combinatorial background.

- The HFT enables high-precision reconstruction of the \( D^0 \) decay vertex, which allows for rejection of background.

\[ m_{D^0} = 1864.84 \pm 0.05 \text{ MeV}/c^2 \quad \text{(PDG)} \]
Sources of Systematic Uncertainties

- **D⁰ Reconstruction**
  - B-meson feed down
  - Varying D⁰ reconstruction topological cuts (e.g. decay length)
  - Extraction of D⁰ signal and background yields
  - Varying position and width of sidebands for background

- **Fitting**
  - Varying model elements in fit
  - Best fits from various binning options on (Δη,Δϕ)

- **Other important contributions**
  - D* Correction
  - Secondary hadrons
  - Pileup (estimated from di-hadron correlations)
Removing D* Contamination

• We form an analogous correlation to our normal correlations.
  • The associated soft pion ($\pi_{soft}^{\pm}$):
    • $.143 \text{ GeV} < M_{K\pi\pi-soft} - M_{K\pi} < .148 \text{ GeV}$ (i.e. within the peak window for the D*).
    • Must be HFT-track (same as other associated cuts).
  • This combination of same-event and mixed-event $D^0$-candidate+$\pi_{soft}^{\pm}$ pairs are normalized and acceptance-corrected in the same way as the normal correlations, and the D* invariant mass background is removed.
• This correlation is subtracted from the $D^0$ “signal region” correlations.
Relevant Kinematic Variables

Instead of the polar angle, which is not Lorentz-invariant, we use the Pseudorapidity: \( \eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right] \), which is the rapidity in the high-energy limit, and is dependent on the polar angle.

**Centrality:** a measure of the overlap of the colliding nuclei via track multiplicity or deposited energy. We cannot directly measure the impact parameter, b.

\( x \)-\( y \) plane: “transverse plane”
\[ \phi = \text{azimuthal angle} \]

**Transverse Momentum:**
\[ p_t = \sqrt{p_x^2 + p_y^2} \]
Deriving our D⁰-Hadron correlation measure

\[ C_{\text{signal}} = C_{D^0+h} + C_{BG+h} + C_{D^*\rightarrow D^0+\pi_{soft}} \]

Where “C” refers to the number of true correlated pairs (e.g. \( C = SE - \alpha ME \)), and “signal” refers to pairs with triggers from the red-band, BG refers to BG triggers from the invariant mass spectrum and the D* term refers to the \( D^0 + \pi_{soft} \) pair from a D* decay.

\[ \text{corr.} = \frac{C_{D^0+h}}{ME_{D^0+h}} = \frac{C_{\text{signal}}}{ME_{D^0+h}} - \frac{C_{BG+h}}{ME_{D^0+h}} - \frac{C_{D^*\rightarrow D^0+\pi_{soft}}}{ME_{D^0+h}} \]

\[ \frac{C_{\text{signal}}}{ME_{D^0+h}} = \frac{\alpha_{\text{signal}} ME_{\text{signal}}}{ME_{D^0+h}} \]

\[ \frac{C_{BG+h}}{ME_{D^0+h}} = \frac{\alpha_{BG+h} ME_{BG+h}}{ME_{D^0+h}} \]

\[ \frac{C_{D^*\rightarrow D^0+\pi_{soft}}}{ME_{D^0+h}} = \frac{\alpha_{D^*\rightarrow D^0+\pi_{soft}} ME_{D^*\rightarrow D^0+\pi_{soft}}}{ME_{D^0+h}} \]

[Diagram and equations]
A simple mathematical model to fit the data

- We started with a simple fit-model with 8 parameters:
  
  \[
  A_0 + 2A_Q \cos(2\Delta \varphi) + A_{SS} e^{\frac{1}{2} \Delta \eta^2} * e^{\frac{1}{2} \Delta \phi^2} + A_{AS} e^{\frac{1}{2} \Delta \eta^2} * e^{\frac{1}{2} (\Delta \phi - \pi)^2} + \text{periodicity for } \Delta \varphi \text{ Gaussian}
  \]

Constant-offset \quad Quadrupole \quad near-side 2D Gaussian \quad Away-Side 2D Gaussian

Note: if the away-side is very broad on \(\Delta \varphi\) (\(\sigma_{\Delta \varphi} \sim 1 \text{ or more}\)), the Gaussian limits to a “dipole” (i.e. \(A_D \cos(\Delta \varphi)\)) due to its periodicity.
Relating the Quadrupole Amplitude ($A_Q$) to $v_2$

\[
\frac{dN}{d\varphi} = 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\varphi - \Psi_R)) \quad \text{Fourier decomposition of single-particle distribution on } \varphi.
\]

\[
\left\langle \frac{dN_D}{d\varphi} \frac{dN_h}{d\varphi} \right\rangle_{\psi} = \left\langle \left( 1 + 2 \sum_{n=1}^{\infty} v_n^D \cos(n(\varphi_D - \Psi_R)) \right) \left( 1 + 2 \sum_{n=1}^{\infty} v_n^h \cos(n(\varphi_h - \Psi_R)) \right) \right\rangle
\]

Average of the product of the single-particle distributions over all the reaction-plane angles in all events.

This is an azimuthal, two-particle correlation.

\[
= 1 + 2 \sum_{n=1}^{\infty} v_n^D v_n^h \cos(n(\varphi_D - \varphi_h)) \quad \varphi_D - \varphi_h \equiv \Delta \varphi
\]

\[
= 1 + 2v_2^D v_2^h \cos(2\Delta \varphi) + \cdots
\]

This $n=2$ term is exactly the quadrupole term used in the multi-parameter fit.
Calculating NS Associated Yield from Fit Parameters

\[ \frac{\Delta \rho^{D_0}}{\rho^{D_0}_{\text{ref}}} = \frac{\sum \text{events} \left( n_{\text{pairs, same}}(\Delta \eta, \Delta \varphi) - \beta n_{\text{pairs, mix}}(\Delta \eta, \Delta \varphi) \right)}{2N_{\text{events}}(n_{D_0})(n_{\text{hadrons}}) \frac{1}{N_{\Delta \varphi} N_{\Delta \eta}} \left( 1 - \frac{|\Delta \eta|}{f_{\eta, \text{accept}}} \right)} \]

To get the NS associated yield, we want to integrate the NS peak.

\[ = \frac{N_{\Delta \varphi} N_{\Delta \eta}}{2N_{\text{events}}(n_{D_0})(n_{\text{hadrons}})} \sum_{\Delta \eta \Delta \varphi: \text{NS Peak}} \left[ \frac{\sum \text{events} \left( n_{\text{pairs, same}}(\Delta \eta, \Delta \varphi) - \beta n_{\text{pairs, mix}}(\Delta \eta, \Delta \varphi) \right)}{1 - \frac{|\Delta \eta|}{f_{\eta, \text{accept}}} \delta_{\Delta \varphi} \delta_{\Delta \eta}} \right] \]

NS Associated yield

\[ Y_{\text{NS,Assoc.}} \approx \frac{2(n_{\text{hadrons}})}{N_{\Delta \varphi} N_{\Delta \eta}} \frac{1}{\delta_{\Delta \varphi} \delta_{\Delta \eta}} \int \int d\Delta \eta d\Delta \varphi A_{\text{NS e}} \frac{1}{2 \sigma_{ss \Delta \eta}} \frac{1}{2 \sigma_{ss \Delta \varphi}} \left[ \Delta \rho^{D_0} \right]_{\text{NS Peak}} \]

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