Characterizing the away-side jet with robust flow background subtraction via two- and three-particle correlations in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV in STAR

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Motivation

- Energetic partons lose energy due to interactions in the dense medium.

Measurements of medium modifications of jets have so far been obscured by the large anisotropic flow background. Flow background decreases with $p_T$. Flow shape and amplitude are not precisely known.

- All orders of $v_n$ are possible and need to be subtracted.
- We devise a method to subtract flow background using data.

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Possible effects of jet-medium interactions

- Nuclear $k_T$ effect
- Event averaging of away-side jets deflected by medium flow
- Collective medium excitation by Mach cone shock waves
\[ P_x |_{\eta_2} = \sum_{\eta_1 < \eta < \eta_2} p_T \cdot \cos(\phi - \phi_{\text{trig}}) \cdot \frac{1}{\varepsilon} \]

\( \varepsilon \): single-particle acceptance \( \times \) efficiency

- For each centrality, cut on the left tail of the distribution (fraction of events) to enhance away-side jet population.
Methodology for two-particle correlations

Trigger particle $|\eta| < 1$

- Select events with a large recoil momentum ($P_x$) within a given $\eta$ window (cartoon 0.5<$\eta$<1) from a high-$p_T$ trigger particle to enhance away-side jet population
- Analyze di-hadron correlations in close-region and far-region respectively
- Flow contributions to close-region and far-region are equal

$$\text{close-region 2p corr.} = \text{flow} + \text{near-side jet} + \text{away-side jet} \times \text{fraction}_\text{close}$$
$$\text{far-region 2p corr.} = \text{flow} + \text{near-side jet} + \text{away-side jet} \times \text{fraction}_\text{far}$$
STAR Au+Au 200 GeV

• Near-side almost equal as expected
• Flow backgrounds are the same in close-region and far-region, cancelled in their difference
• Quantify the shape by Gaussian fit $\sigma$

close-region 2p corr. = flow + near-side jet + away-side jet $\times$ fraction_close
far-region 2p corr. = flow + near-side jet + away-side jet $\times$ fraction_far

$3<p_T^{\text{trig}}<10$ GeV/c
$2<p_T^{\text{assoc}}<3$ GeV/c

STAR preliminary

STAR TPC

close-region
far-region
away-side jet

$\chi^2/\text{ndf}$ 34.3/46
Away-side jet correlation shape

- The correlation shape is consistent with Gaussian.
Away side jet correlation width

Away-side jets are modified:
- Moderate to high $p_T$ associated particles: broaden with increasing centrality
- Shape for all $p_T$ more similar in central than in peripheral collisions

The horizontal caps indicate the systematic error
Comparison to pp and dAu

- Peripheral data are consistent with pp/dAu

The leftmost 3 sets of data are for
PHENIX p+p
PHENIX d+Au
STAR d+Au Minbias

pp and dAu:
No $P_x$ cut is applied.
Momentum cuts in the ref. are slightly different

• Peripheral data are consistent with pp/dAu
Methodology for three-particle correlations

Suppose an event is composed of: (besides the High-$p_T$ trigger particle $T$)

- **A**: Jets correlated with the trigger (di-jet)
- **f**: flow background
- **a**: jets uncorrelated with the trigger

**same \( \eta \)-region pairs**

\[ T_{AA} + T_{Af} + T_{Aa} + T_{fA} + T_{ff} + T_{fa} + T_{Ta} + T_{af} + T_{aa} \]

(signal + combinatorial bkg + bkg jets)

**cross \( \eta \)-region pairs**

\[ T_{Af} + T_{Aa} + T_{fA} + T_{ff} + T_{fa} + T_{Ta} + T_{af} \]

(combinatorial bkg)

**same \( \eta \)-region pairs - cross \( \eta \)-region pairs**

\[ T_{AA} + T_{aA} \] (signal + bkg jets)

Two lower $p_T$ associated particles

No $P_x$ cut is applied in 3-p correlations
Background jets in triggered events = jets in min-bias events
(no requirement of a trigger, normalized per event)

• Suppose the number of jets is Poisson distributed with an average of $\lambda$. The probability to have $n$ jets per event is

$$P_n = \frac{\lambda^n e^{-\lambda}}{n!}$$

The probability of having a trigger particle with $(n-1)$ background jets is

$$nP_n / \sum_{m=1}^{\infty} mP_m = \frac{\lambda^{n-1} e^{-\lambda}}{(n-1)!} = P_{n-1}$$

This is identical to the probability to have $(n-1)$ jets per event for minbias events

• We can construct the jet background Taa by min-bias events w.r.t. a random “trigger” $\phi$
Three-particle azimuthal correlations

$3 < p_T^{\text{trig}} < 10 \text{ GeV/c}, \quad 2 < p_T^{\text{assoc}} < 3 \text{ GeV/c}$

$60-80\% \text{ Au+Au}$

- TAA + Taa: Same $\eta$-region correlations - cross $\eta$-region correlations
- Taa: Background jet correlations
- TAA: Background-subtracted three-particle correlations

- What’s left in three-particle correlations are the short range correlations on both the near side and away side
Intra-jet and inter-jet correlation width

- Away side: inter-jet correlation >> intra-jet correlation → significant $k_T$ and/or flow deflection.
- Intra-jet correlation: $\sigma$ near = away and no centrality dependence → little jet modification?
- Requirement of a trigger ($p_T > 3$ GeV/c) and two associated particles ($2 < p_T < 3$ GeV/c) bias towards unmodified jets?
Conclusions

• Novel methods were devised to measure away-side jet correlations with clean, robust flow subtraction using data.
• Away-side jets are modified
  – Correlation broadens with centrality except low $p_T$
• Three-particle azimuthal correlations
  – Away-side: inter-jet correlations is significantly broader than intra-jet correlations $\rightarrow$ significant $k_T$ and/or flow deflection.
  – Intra-jet correlations: similar between near- and away-side, and no centrality dependence is found. $\rightarrow$ Little jet-shape modification on the away side?
  – $p_T$ cuts bias towards unmodified jets?
Thank you!
Backup slides
Correct for $\phi$-dependent acceptance $\times$ efficiency

- Normalize the single particle $\phi$ distribution to average unity. The inverse of that will be the $\phi$-dependent efficiency
- Done run-by-run (and runs with same efficiency grouped together)
- Corrections are done as a function of centralities
- Apply $\phi$-dependent efficiency correction for $P_x$ calculation and di-hadron correlations
Correct for $\eta$-dependent acceptance $\times$ efficiency

- Treat symmetrized $dN/d\eta$ distribution in events with $|z_{vtx}| < 2$ cm as the baseline
- Take the inverse of the ratio of the $dN/d\eta$ distribution from each $z_{vtx}$ bin to this baseline
- Apply $\eta$-dependent efficiency correction for $P_x$ calculation and di-hadron correlations
Systematic study

- Vary $P_x$ cut to vary the relative contributions of jets and background fluctuations to the selected events.
  - From allowing 10% of events to 2%, 5%, 15%, 20%, 30%, 50% of events.
  - Assign a systematic error of 3.2% from $P_x$ cut

- Vary track quality cut
  - A systematic error of 1.5% from dca (distance of closest approach to the collision vertex)
  - A systematic error of 2.0% from nhitsfit (number of TPC hits)
Systematic study

- Vary the close- and far-region $\eta$ window locations and ranges, vary $P_x$
- $\eta$ window location and range
  - Effects of flow may be decorrelated over $\eta$ due to geometry fluctuations
  - The largest deviation of $\sigma$ from the default results is approximately half of the statistical error
  - Assign a systematic error of 2.5% as another source of systematic uncertainty

<table>
<thead>
<tr>
<th>Set 0, 1, 2</th>
<th>Set 0, 1</th>
<th>Set 0, 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Vary close- and far-</td>
<td>-0.10 +/- 0.17</td>
<td>0.44 +/- 0.16</td>
</tr>
<tr>
<td>2. Vary close- and far- (with $\eta$ gap)</td>
<td>0.00 +/- 0.13</td>
<td>0.34 +/- 0.17</td>
</tr>
<tr>
<td>3. Vary $P_x$</td>
<td>-0.21 +/- 0.20</td>
<td>-0.50 +/- 0.27</td>
</tr>
<tr>
<td>4. New $P_x$, Vary close- and far-</td>
<td>0.00 +/- 0.15</td>
<td>0.11 +/- 0.21</td>
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## Systematic study

### Summary of systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Percent</th>
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<tbody>
<tr>
<td>$P_x$</td>
<td>3.2%</td>
</tr>
<tr>
<td>dca</td>
<td>1.5%</td>
</tr>
<tr>
<td>nhitsfit</td>
<td>2.0%</td>
</tr>
<tr>
<td>$\eta$ windows</td>
<td>2.5%</td>
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</tbody>
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Intra-jet and inter-jet correlations

Off-diagonal projection: intra-jet correlations
Diagonal projection: inter-jet correlations

\[ \Sigma = (\Delta \phi_1 + \Delta \phi_2)/2 - \pi \text{ (away-side)} \]
\[ \Delta = (\Delta \phi_1 - \Delta \phi_2)/2 \]

- Projections of near-side and away-side three-particle correlations along the diagonal \( \Sigma \) within \( 0 < \Delta < 0.35 \) and off-diagonal \( \Delta \) within \( |\Sigma| < 0.35 \).
**Intra-jet and inter-jet correlation width: near-side**

Systematic errors are estimated by varying track quality cuts.

- **Near-side**: $\sigma_{\text{diag}} > \sigma_{\text{off-diag.}} \rightarrow \text{jet axis swing effect?} (\text{the trigger and the two associated particles are likely on different sides of the jet axis})
The $v_2$ and $v_4$ background subtracted three-particle correlations. 12% central Au+Au