Jet shapes and fragmentation functions in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in STAR

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Quark Matter 2019, Parallel Session – Jet Modifications I
November 5th, 2019
Introduction

- Jets probe the strongly interacting QCD medium
  - Hard-scattered partons generated at the early stages of heavy-ion collisions
  - Interactions between jets and the QCD medium modify the parton shower relative to that in vacuum

How is the parton shower changed in A+A?

Introduction

- Jets probe the strongly interacting QCD medium
  - Hard-scattered partons generated at the early stages of heavy-ion collisions
  - Interactions between jets and the QCD medium modify the parton shower relative to that in vacuum

How is the parton shower changed in A+A?

How does the fragmentation of jets change in heavy-ion collisions?

How does the internal energy distribution of jets change in heavy-ion collisions?
Jet shapes and FFs in STAR – Saehanseul Oh

**Jet Shapes**

- $r = \sqrt{(\Delta \varphi)^2 + (\Delta \eta)^2}$

**Jet Fragmentation Functions**

- Fragmentation function\(^1\), $\frac{1}{N_{\text{jet}}} \frac{dN}{dz}$
- Distribution of longitudinal momentum fraction of particles with respect to the jet

1. The name of this function is following the convention in relativistic heavy ion physics, although there is a more standard definition: http://pdg.lbl.gov/2019/reviews/rpp2018-rev-frag-functions.pdf
Jet Fragmentation Functions

• Fragmentation function, \( \frac{1}{N_{\text{jet}}} \frac{dN}{dz} \)
• Distribution of longitudinal momentum fraction of particles with respect to the jet

Jet Shapes

\[ \rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{track}} \sum \frac{\Sigma_{\text{track} \in (r-\delta r/2, r+\delta r/2) P_{T,\text{track}}}}{P_{T,\text{jet}}} \]

• Distribution of jet energy as a function of distance from the jet axis
Introduction

Jet Fragmentation Functions

- Fragmentation function, \( \frac{N_{jet}}{dz} \)
- Distribution of longitudinal momentum fraction of particles with respect to the jet

Jet Shapes

- Distribution of jet energy as a function of distance from the jet axis

\[ \sqrt{s_{NN}} = 200 \text{ GeV?} \]
Jet measurements in A+A

- Challenge in jet measurements in A+A → Large fluctuating background
Jet measurements in A+A

- Challenge in jet measurements in A+A → **Large fluctuating background**

Semi-inclusive measurement with ME

Hard-core vs. matched jets

$\mathbf{p_T^{\text{Cut}} = 2 \text{ GeV/c}}$

$\mathbf{p_T^{\text{Cut}} = 0.2 \text{ GeV/c}}$


Jet measurements in A+A

- Challenge in jet measurements in A+A → Large fluctuating background

Semi-inclusive measurement with ME

Used in the jet fragmentation function measurement

Jets in the recoil region of a high momentum particle (semi-inclusive approach)
Jet measurements in A+A

- Challenge in jet measurements in A+A $\rightarrow$ **Large fluctuating background**

Jet reconstruction with high $p_T$ constituents (HardCore jet)

Used in the jet shape measurement
The STAR experiment

- Time Projection Chamber
- $|\eta| < 1.0$, $0 < \varphi < 2\pi$
- Momentum, $dE/dx$

<table>
<thead>
<tr>
<th>BEMC</th>
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<td>• Barrel Electromagnetic Calorimeter</td>
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<td>• Trigger</td>
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EM neutral constituents

Charged constituents

Full Jet

Charged Jet

Jet shapes and FFs in STAR – Saehanseul Oh
The STAR experiment

**TPC**
- Time Projection Chamber
- $|\eta| < 1.0, 0 < \varphi < 2\pi$
- Momentum, $dE/dx$

**BEMC**
- Barrel Electromagnetic Calorimeter
- $|\eta| < 1.0, 0 < \varphi < 2\pi$
- Trigger

**EM neutral constituents**

**Charged constituents**

**Full Jet**

**Charged Jet**

- 2014, Au+Au, $\sqrt{s_{NN}} = 200$ GeV
- Minimum-bias + high-tower triggered events
- Mixed events for the background estimation – for each (centrality, $z_{vtx}$, $\Psi_{EP}$, track multiplicity) bin with minimum-bias events
Jet Fragmentation Functions
Jet fragmentation functions

\[ z = \frac{p_{T,\text{track}} \cos(r)}{p_{T,\text{jet}}} \]

\[ \frac{1}{N_{\text{jet}}(p_{T,\text{jet}})} \frac{dN_{p_{T,\text{jet}},z}}{dz} \]

for tracks within \( \Delta r_{\text{jet-track}} < R = 0.4 \)
Jet shapes and FFs in STAR – Saehanseul Oh

Jet fragmentation functions

- \( Z = \frac{p_{T,\text{track}} \cos(r)}{p_{T,\text{jet}}} \)
- \( \frac{1}{N_{\text{jet}}(p_{T,\text{jet}})} \frac{dN(p_{T,\text{jet}},z)}{dz} \) for tracks within \( \Delta r_{\text{jet-track}} < R = 0.4 \)

- **Charged jets** are selected in the recoil region with respect to high momentum trigger particles (semi-inclusive approach, BEMC tower with \( 9.0 < E_T < 30.0 \text{ GeV} \), \( |\varphi_{\text{trig}} - \varphi_{\text{jet}}| > \pi - \pi/4 \))
Jet fragmentation functions – Corrections

\[ z = \frac{p_{T,\text{track}} \cos(r)}{p_{T,\text{jet}}} \]

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for tracks within \( \Delta r_{\text{jet-track}} < R = 0.4 \)

- In the recoil region, there are two types of jets
  - **Signal (Sig.) jet**, i.e. jets correlated to the trigger particle
  - **Background (Bkg.) jet**, i.e. jets uncorrelated to the trigger particle
  - In signal jets, there are uncorrelated particles
Jet fragmentation functions – Corrections

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- In signal jets, there are uncorrelated particles

**How can we remove the uncorrelated components?**
Jet shapes and FFs in STAR – Saehanseul Oh

Jet fragmentation functions – Corrections

\[ z = \frac{p_{T,\text{track}} \cos(r)}{p_{T,\text{jet}}} \]

\[ \frac{1}{N_{\text{jet}}(p_{T,\text{jet}})} \frac{dN}{dz} \text{ for tracks within } \Delta r_{\text{jet-track}} < R = 0.4 \]

- \( N_{\text{jet}}(p_{T,\text{jet}}) = N_{\text{jet}}^{\text{SE}}(p_{T,\text{jet}}) - N_{\text{jet}}^{\text{ME}}(p_{T,\text{jet}}) \)
  - Jets reconstructed in same-events
  - Jets reconstructed in mixed-events

- \( N_{\text{jet}}^{\text{ME}}(p_{T,\text{jet}}) \) are fitted to \( N_{\text{jet}}^{\text{SE}}(p_{T,\text{jet}}) \) in the negative \( p_{T,\text{jet}} \) range, where uncorrelated jets are expected to dominate (STAR, Phys. Rev. C 96 (2017) 24905)
Jet shapes and FFs in STAR – Saehanseul Oh

Jet fragmentation functions – Corrections

\[ z = \frac{p_{T,\text{track}} \cos(r)}{p_{T,\text{jet}}} \]

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Jets reconstructed in same-events

Jets reconstructed in mixed-events

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Sig. jet

Bkg. jet

Correlated particle

Uncorrelated particle

Removing Bkg. jet in \( N_{\text{jet}} \)
Jet fragmentation functions – Corrections

\[ z = \frac{p_{T,\text{track}} \cos(r)}{p_{T,\text{jet}}} \]

\[ \frac{1}{N_{\text{jet}}(p_{T,\text{jet}}, z)} \frac{dN(p_{T,\text{jet}}, z)}{dz} \] for tracks within \( \Delta r_{\text{jet-track}} < R = 0.4 \)

- The fraction of background jets to the all jets can be estimated by comparing \( N_{\text{jet}}^{\text{ME}}(p_{T,\text{jet}}) \) and \( N_{\text{jet}}^{\text{SE}}(p_{T,\text{jet}}) \)
- Contributions from background jets in \( dN(p_{T,\text{jet}}, z)/dz \) can be calculated by \( dN_{\text{ME}}(p_{T,\text{jet}}, z)/dz \) and scaling it based on the background jet fraction
- Contributions from uncorrelated particles in signal jets can be estimated by placing SE jets into mixed events and pairing with ME tracks
The fraction of background jets to the all jets can be estimated by comparing \( N_{jet}^{ME} (p_{T,jet}) \) and \( N_{jet}^{SE} (p_{T,jet}) \).

Contributions from background jets in \( dN (p_{T,jet}, z)/dz \) can be calculated by \( dN^{ME} (p_{T,jet}, z)/dz \) and scaling it based on the background jet fraction.

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Jet shapes and FFs in STAR – Saehanseul Oh

Jet fragmentation functions – Corrections

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Jet shapes and FFs in STAR – Saehanseul Oh

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Jet fragmentation functions – Corrections

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Jet shapes and FFs in STAR – Saehanseul Oh
Jet fragmentation functions – Results

Jet shapes and FFs in STAR – Saehanseul Oh

Jet fragmentation functions for 40-60% centrality class and three $p_T$ ranges

• $N_{jet}(p_{T,\text{jet}})$ and $dN(p_{T,\text{jet}},z)/dz$ are separately unfolded via 1-D and 2-D Bayesian unfolding

• $1/N_{jet} \cdot \frac{dN(p_{T,\text{jet}},z)}{dz}$
Jet fragmentation functions – Results

\[ \frac{1}{N_{\text{jet}}} \frac{dN}{dz}(p_{T,\text{jet}}, z) = \frac{dN}{dz} \]

- Jet shapes and FFs in STAR – Saehanseul Oh

Jet fragmentation functions for 40-60% centrality class and three \( p_{T,\text{jet}} \) ranges

- Fragmentation function prior variations in unfolding are not included in the systematic uncertainties
- PYTHIA 8 is tuned to LHC, and needs further parameter tuning (More details in Raghav Kunnawalkam Elayavalli’s talk, Wed. 9:20)
Jet fragmentation functions – Results

- Ratios of jet fragmentation functions, (Au+Au 40-60%)/(PYTHIA 8)
- The ratio remains near 1 → Tangential jet selection with a high-$p_T$ trigger particle and recoil jets? Less jet-medium interactions in 40-60% centrality? Short path-length in medium in 40-60% centrality? …
- Results for p+p and central events and overall higher statistics are on their way
Jet shapes and FFs in STAR – Saehanseul Oh

Jet fragmentation functions – Results

- Ratios of jet fragmentation functions, \((\text{Au+Au 40-60%})/(\text{PYTHIA 8})\)
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- Results for \(p+p\) and central events and overall higher statistics are on their way
Jet Shapes

**Poster 354 (JT12).** "Evolution of jet shapes in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV with the STAR detector at RHIC", Joel Mazer (Rutgers University)
Jet shapes

\[ \rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{track} \in (r-\delta r/2, r+\delta r/2)} p_{T,\text{track}}}{p_{T,\text{jet}}} \]

- Full (charged + neutral) jets are reconstructed with high-momentum tracks and towers with \( p_{T,\text{track}}(E_{T,\text{tower}}) > 2.0 \text{ GeV}/c \) (HardCore jet selection)
- Background contributions in \( \rho(r) \) are estimated by placing same-event jets (\( p_{T,\text{jet}} \) and jet axis) in mixed-events. \( \rho_{\text{ME}}(r) \) is calculated and then subtracted from \( \rho(r) \), accordingly.
Jet shapes

\[
\rho(r) = \frac{1}{\delta r N_{\text{jet}}} \sum_{\text{track} \in (r-\delta r/2, r+\delta r/2)} \frac{p_{T,\text{track}}}{p_{T,\text{jet}}}
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Jet shapes – Results

- Jet shapes for 0-10% centrality
- At low $p_T$, background contributions dominate $\rho(\Delta r)$

![Graph showing jet shapes and FFs in STAR](STAR Preliminary)

Jet shapes and FFs in STAR – Saehanseul Oh

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Jet shapes – Results

- Jet shapes for 0-10% centrality
- At low $p_{T,\text{jet}}$, background contributions dominate $\rho(r)$

**STAR Preliminary**

**Leading jets**

- $\sqrt{s_{NN}} = 200$ GeV, 0-10%
- Anti-$k_T$, full jets, $R=0.4$
- $p_{T \text{unc, jet}}^{\text{ch+ne}} = 20-40$ GeV/c
- $p_T^c, E_T^c > 2.0$ GeV

**Jet shapes and FFs in STAR** – Saehanseul Oh
Jet shapes – Results

- Jet shapes for 0-10% centrality after background subtraction
- High-$p_T$ tracks are located near the jet axis compared to low-$p_T$ tracks as expected
- Jet shapes are less steep at 200 GeV than those at the LHC
Jet shapes – Results

- Jet shapes for 0-10% centrality after background subtraction
- High-$p_T$ tracks are located near the jet axis compared to low-$p_T$ tracks as expected
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Jet shapes and FFs in STAR – Saehanseul Oh
Jet shapes – Results

- Jet shapes for 0-10% centrality after background subtraction
- High-$p_T$ tracks are located near the jet axis compared to low-$p_T$ tracks as expected
- Jet shapes are less steep at 200 GeV than those at the LHC
Jet shapes – Event-plane dependence

- Jet shapes can be measured more differentially based on jets’ azimuthal angle relative to the 2nd-order event plane (EP)
  - In-plane: $0^\circ \leq |\phi_{\text{jet}} - \Psi_{\text{EP}}| < 30^\circ$
  - Mid-plane: $30^\circ \leq |\phi_{\text{jet}} - \Psi_{\text{EP}}| < 60^\circ$
  - Out-of-plane: $60^\circ \leq |\phi_{\text{jet}} - \Psi_{\text{EP}}| < 90^\circ$

- Jets may experience different in-medium path length effects depending on their direction relative to the $\Psi_{\text{EP}}$

- Event-plane dependent results are corrected for the EP resolution effects
  - More details about the resolution correction at Poster 354 (JT12). “Evolution of jet shapes in Au+Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV with the STAR detector at RHIC”, Joel Mazer (Rutgers University)
Jet shapes – Results

Leading Jets
EP resolution corr.

20-50% Centrality
Au+Au: \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

In-plane
Mid-plane
Out-of-plane

Anti-\( k_t \) full jets, \( R=0.4 \)
\( p_T^{\text{chane}} \)
\( T \) unc, jet
\( p_T^{ch}, E_T^{clus} > 2.0 \text{ GeV} \)

\( \rho(r) \)

20-50% Centrality
Au+Au: \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

In-plane
Mid-plane
Out-of-plane

Anti-\( k_t \) full jets, \( R=0.4 \)
\( p_T^{\text{chane}} \)
\( T \) unc, jet
\( p_T^{ch}, E_T^{clus} > 15-20 \text{ GeV} \)

\( \rho(r) \)

20-50% Centrality
Au+Au: \( \sqrt{s_{NN}} = 200 \text{ GeV} \)

In-plane
Mid-plane
Out-of-plane

Anti-\( k_t \) full jets, \( R=0.4 \)
\( p_T^{\text{chane}} \)
\( T \) unc, jet
\( p_T^{ch}, E_T^{clus} > 20-40 \text{ GeV} \)

\( \rho(r) \)
Jet shapes – Results

**In-plane**

20-50% Centrality

**Mid-plane**

20-50% Centrality

**Out-of-plane**

20-50% Centrality

\[ p_{T \text{unc, jet}}^{\text{ch+ne}} = 10-15 \text{ GeV/c} \]

\[ p_{T \text{unc, jet}}^{\text{ch+ne}} = 15-20 \text{ GeV/c} \]

\[ p_{T \text{unc, jet}}^{\text{ch+ne}} = 20-40 \text{ GeV/c} \]

STAR Preliminary

EP resolution corr.

Leading Jets

\[ 1.0 < p_{T \text{miss}} < 1.5 \text{ GeV/c} \]

\[ 1.5 < p_{T \text{miss}} < 2.0 \text{ GeV/c} \]

\[ 2.0 < p_{T \text{miss}} < 3.0 \text{ GeV/c} \]

\[ 3.0 < p_{T \text{miss}} < 4.0 \text{ GeV/c} \]

\[ 4.0 < p_{T \text{miss}} < 6.0 \text{ GeV/c} \]

\[ p_{T \text{miss}} > 6.0 \text{ GeV/c} \]

Total: \( p_{T \text{miss}} > 1.0 \times \text{GeV/c} \)
Jet shapes – Results

Leading Jets
EP resolution corr.

In-plane
Mid-plane
Out-of-plane

1.0 < $p_T^{\text{assoc}}$ < 1.5 GeV/c
1.5 < $p_T^{\text{assoc}}$ < 2.0 GeV/c
2.0 < $p_T^{\text{assoc}}$ < 3.0 GeV/c
3.0 < $p_T^{\text{assoc}}$ < 4.0 GeV/c
4.0 < $p_T^{\text{assoc}}$ < 6.0 GeV/c
$p_T^{\text{assoc}}$ > 6.0+ GeV/c
Total: $p_T^{\text{assoc}}$ > 1.0+ GeV/c

20-50% Centrality
Au+Au: $s_{NN}$ = 200 GeV

20-50% Centrality
Au+Au: $s_{NN}$ = 200 GeV

Anti-$k_t$ full jets, R=0.4

$p_T^{\text{chne}}$, $E_T^{\text{clus}}$ >2.0 GeV

$p_T^{\text{chne}}$, $E_T^{\text{clus}}$ >2.0 GeV

STAR Preliminary
Jet shapes – Results

- Jets with higher $p_T,\text{jet}$ are more collimated.
Jet shapes – Results

- Low-$p_T$ tracks are pushed toward farther distances in the out-of-plane direction relative to the in-plane direction.
- Larger yields of low-$p_T$ tracks in the out-of-plane direction.

→ Larger effects in the out-of-plane direction due to longer in-medium path length?
Summary

Jet fragmentation functions
- Recoil jets with respect to a high momentum trigger particle in 40-60% centrality are studied
- The unfolded fragmentation function results for three $p_{T,\text{jet}}$ ranges are comparable to PYTHIA 8, but PYTHIA 8’s reliability at RHIC energies is limited
- Results for central and $p+p$ events are on their way

Jet shapes
- Full jets with a high-momentum constituent cut are utilized in jet finding
- In the event-plane dependent measurements, low-$p_T$ tracks have larger yields and pushed toward farther distances in the out-of-plane direction → Sensitivity on the path-length dependence of jet quenching
- Results for $p+p$, different centralities, and different jet $R$ are on their way
Backup slides
Jet fragmentation functions @5.02 TeV

Figure 15: Ratios of $(D(\bar{c}))$ distributions in six centrality intervals of Pb+Pb collisions to $pp$ collisions evaluated in four $p_T^{jet}$ ranges for jets with $1.2 < |y| < 2.1$. The vertical bars on the data points indicate statistical uncertainties, while the shaded bands indicate systematic uncertainties. Centrality decreases from top to bottom panels and $p_T^{jet}$ increases from left to right panels.

Figure 16: Ratios of $(D(\bar{c}))$ distributions in six centrality intervals of Pb+Pb collisions to $pp$ collisions evaluated in four $p_T^{jet}$ ranges for jets with $|y| < 0.3$. The vertical bars on the data points indicate statistical uncertainties, while the shaded bands indicate systematic uncertainties. Centrality decreases from top to bottom panels and $p_T^{jet}$ increases from left to right panels.

Jet shapes @2.76 TeV
Analyses details

- In the presented measurements
  - 2014, Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV
  - Minimum-bias + high-tower triggered events
  - Anti-$k_T$ algorithm for jet reconstruction with $R = 0.4$ and $|\eta_{jet}| < 1.0 - R$
  - In the jet shape measurement,
    - HardCore $p_{T,\text{jet}}$ is estimated without a $\rho A$ subtraction
    - Mixed event class is defined with centrality, $z_{vtx}$, $\Psi_{EP}$, track multiplicity bins. There are 14 $z_{vtx}$ bins, 4 $\Psi_{EP}$ bins, and 16 multiplicity bins in each centrality
  - In the fragmentation function measurement,
    - Raw $p_{T,\text{jet}}$ is estimated with a $\rho A$ subtraction, where $\rho$ is estimated from jets reconstructed with the $k_T$ algorithm
    - Mixed event class is defined with centrality, $z_{vtx}$, $\Psi_{EP}$, track multiplicity bins. There are 15 $z_{vtx}$ bins, 4 $\Psi_{EP}$ bins, and 8 multiplicity bins in each centrality
    - In fragmentation function unfolding, detector effects are simulated with Fast Simulation (efficiency and momentum resolution)