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

Joel Mazer (Rutgers University) for the STAR Collaboration

Hard Probes 2020, Parallel Session – Jets and High Momentum Hadrons
June 4th, 2020
Introduction

- Jets are a useful probe for studying the QGP
  - Resultant of 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

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How is the parton shower changed in A+A?

How does the **internal energy distribution** of jets change in heavy-ion collisions?

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

Jet

Jet shapes and FFs in STAR – Joel Mazer

Jet Fragmentation Functions

Jet Fragmentation Function

Jet

Constituent Particle

Provides information about the radial distribution of momentum carried by the jet constituents (fragments)

\[ r = \sqrt{(\Delta \varphi)^2 + (\Delta \eta)^2} \]

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

Provides information of the longitudinal momentum fraction of particles with respect to the jet

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

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
Introduction - LHC results

Jet Shapes

\[ r = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} \]

Jet Fragmentation Functions

[Graphs showing jet shapes and fragmentation functions]

Pb+Pb/p+p @ 2.76 TeV

Pb+Pb/p+p @ 5.02 TeV

Jet shapes and FFs in STAR - Joel Mazer
At $\sqrt{s_{NN}} = 200$ GeV?
Jet measurements in A+A

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

Hard-core vs. matched jets

\[ p_T^{\text{Cut}} = 2 \text{ GeV}/c \]

\[ p_T^{\text{Cut}} = 0.2 \text{ GeV}/c \]

Semi-inclusive measurement with ME


Jet measurements in A+A

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Hard-core vs. matched jets

- $p_T^{\text{Cut}} = 2 \text{ GeV/c}$
- $p_T^{\text{Cut}} = 0.2 \text{ GeV/c}$

Semi-inclusive measurement with ME


Used in the jet shape measurement

Jet reconstruction with high $p_T$ constituents (HardCore jet)
Jet measurements in A+A

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

Hard-core vs. matched jets

\[ p_T^{\text{Cut}} = 2 \text{ GeV/c} \quad \text{vs.} \quad \ p_T^{\text{Cut}} = 0.2 \text{ GeV/c} \]

Semi-inclusive measurement with ME


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

Used in the jet fragmentation function measurement

Jet shapes and FFs in STAR - Joel Mazer
The STAR experiment

TPC
- Time Projection Chamber:
  - $|\eta| < 1.0$, $0 < \phi < 2\pi$
  - Tracking, momentum, $dE/dx$, event plane reconstruction

BEMC
- Barrel Electromagnetic Calorimeter:
  - $|\eta| < 1.0$, $0 < \phi < 2\pi$
  - Resolution: 0.05x0.05
  - Study high-$p_T$ processes, triggering

Charged constituents
- Full Jet
- Charged Jet
- EM neutral constituents

2014, Au+Au, $\sqrt{s_{NN}} = 200$ GeV
- Minimum-bias (MB) + high-tower (HT) triggered events
- Mixed events for background estimation - for each (centrality/track multiplicity, $z_{vtx}$, $\Psi_{EP}$) bin with MB events
Jet shapes

Gavin Salam – QM 2018
Jet shapes

\[ r = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} \]

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

- Full (charged + neutral) jets reconstructed with high-momentum tracks and towers with \( p_{T,\text{track}} (E_{T,\text{tower}}) > 2.0 \) GeV/c
- (HardCore jet selection)
Jet shapes

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

- Full (charged + neutral) jets 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) into mixed-events. Background jet shape, \( \rho_{\text{ME}}(r) \), is calculated and then subtracted from \( \rho(r) \), accordingly.

Jet shapes and FFs in STAR – Joel Mazer
Jet shapes – Results

STAR Preliminary

Jet shapes for 0-10%

Jet shapes and FFs in STAR – Joel Mazer
Jet shapes – Results

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Jet shapes for 0-10%

At low $p_T^{assoc}$ and for most central collisions background contributions dominate $\rho(r)$

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Jet shapes – Results

Jet shapes for 0-10% centrality after background subtraction

STAR Preliminary

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High-$p_T$ tracks are located near the jet axis compared to low-$p_T$ tracks, as expected
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.

**First differential jet study at RHIC energies**

- Total jet shape for:
  - 20-40 GeV/c jets
  - $p_T^{assoc} > 1.0$ GeV/c
Jet shapes are less steep at 200 GeV than at LHC energies
- With variations in kinematics and jet selection

See talks: Robert Ličeník (#237, 6/1 12:20 ET) & Nihar Sahoo (#238, 6/2 12:20 ET)
Jet shapes – Event-plane dependence

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

- Control path-length of jet quenching with centrality and event-plane angle

- Jets may experience different in-medium path length depending on their direction relative to the $\Psi_{\text{EP}}$
  - Average path-length OUT $>$ average path-length IN

Are we sensitive enough?
Due to finite multiplicity of each event, there will be a difference between the reconstructed event plane and underlying symmetry plane: $\Psi_2$

$$R_n = \langle \cos(n(\psi_{n,\text{true}} - \psi_{n,\text{reco}})) \rangle$$

Using modified reaction-plane (MRP) method, for $p_T$ associated bins

- Improvement over typical EP measurements with the TPC and BBC
- Peak for 20-30% and 30-40% centrality
- Excluding track with $p_T = 0.5$-1.0 GeV/c gives lowest $R_2$

STAR, Phys. Rev. C 89 (2014) 041901(R)
Jet shapes – Results

\[ \rho(r) \]

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

- **In-plane**
  - \( 1.0 < p_T^{\text{ch+ne}} < 1.5 \text{ GeV/c} \)
  - \( 1.5 < p_T^{\text{ch+ne}} < 2.0 \text{ GeV/c} \)
  - \( 2.0 < p_T^{\text{ch+ne}} < 3.0 \text{ GeV/c} \)
  - \( 3.0 < p_T^{\text{ch+ne}} < 4.0 \text{ GeV/c} \)
  - \( 4.0 < p_T^{\text{ch+ne}} < 6.0 \text{ GeV/c} \)
  - Total: \( p_T^{\text{ch+ne}} > 6.0 \text{ GeV/c} \)

- **Mid-plane**
  - Anti-k\_ full jets, R=0.4
  - \( p_T^{\text{ch+ne}} = 10-15 \text{ GeV/c} \)
  - \( p_T^{\text{ch+ne}}, E_T^{\text{clus}} > 2.0 \text{ GeV} \)

- **Out-of-plane**
  - \( 1.0 < p_T^{\text{ch+ne}} < 1.5 \text{ GeV/c} \)
  - \( 1.5 < p_T^{\text{ch+ne}} < 2.0 \text{ GeV/c} \)
  - \( 2.0 < p_T^{\text{ch+ne}} < 3.0 \text{ GeV/c} \)
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  - Total: \( p_T^{\text{ch+ne}} > 6.0 \text{ GeV/c} \)

- **Mid-plane**
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  - \( p_T^{\text{ch+ne}} = 15-20 \text{ GeV/c} \)
  - \( p_T^{\text{ch+ne}}, E_T^{\text{clus}} > 2.0 \text{ GeV} \)

- **Out-of-plane**
  - \( 1.0 < p_T^{\text{ch+ne}} < 1.5 \text{ GeV/c} \)
  - \( 1.5 < p_T^{\text{ch+ne}} < 2.0 \text{ GeV/c} \)
  - \( 2.0 < p_T^{\text{ch+ne}} < 3.0 \text{ GeV/c} \)
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\[ p_T^{\text{ch+ne}} \text{ T unc, jet} \]

- In-plane: \( 10-15 \text{ GeV/c} \)
- Mid-plane: \( 15-20 \text{ GeV/c} \)
- Out-of-plane: \( 20-40 \text{ GeV/c} \)
Jet shapes – Results

Differentially separated further into associated $p_T$ ranges
Jet shapes – Results

Higher $p_{T,\text{jet}}$ are more collimated.
Jet shapes – Results

- Higher $p_T$,jet are more collimated
- For low-$p_T$ associated tracks, out-of-plane jet shape is flatter compared to in-plane
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.

Are the larger effects in the out-of-plane direction due to longer in-medium path length?
Jet shapes and FFs in STAR – Joel Mazer

Poster 248 (JHMH). "Measurement of semi-inclusive jet fragmentation functions in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in STAR", Saehanseul Oh (LBNL)
**Jet fragmentation functions**

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

\[ \frac{1}{N_{\text{jet}}(p_{\text{T,jet}})} \frac{dN(p_{\text{T,jet}},z)}{dz} \]  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, BEMC tower with \( 9.0 < E_T < 30.0 \) GeV), \( |\phi_{\text{trig}} - \phi_{\text{jet}}| > \pi - \pi/4 \)
Jet fragmentation functions

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In the recoil region, there are two types of jets

- **Signal (Sig.) jet**, i.e. jets correlated to the trigger particle
  - These jets also contain *uncorrelated particles*

- **Background (Bkg.) jet**, i.e. jets uncorrelated to the trigger particle
Jet fragmentation functions – Corrections

How can we remove the uncorrelated components?

- $N_{\text{jet}}^{\text{ME}}(p_{T,jet})$ are fitted to $N_{\text{jet}}^{\text{SE}}(p_{T,jet})$ in the negative $p_{T,jet}$ range, where uncorrelated jets are expected to dominate (STAR, Phys. Rev. C 96 (2017) 24905)
  - **Removes Bkg. jets from $N_{\text{jet}}$**

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

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

- Compare $N_{\text{jet}}^{\text{ME}}(p_{T,jet})$ with $N_{\text{jet}}^{\text{SE}}(p_{T,jet})$ to estimate fraction of Bkg. jets
Jet fragmentation functions – Corrections

How can we remove the uncorrelated components?

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

\(N_{\text{jet}}^{\text{ME}}(p_{T,\text{jet}})\) 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)

- **Removes Bkg. jets from \(N_{\text{jet}}\)**

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 background jet fraction

- **Removes Bkg. jets from \(dN(p_{T,\text{jet}}, z)/dz\)**

Contributions from uncorrelated particles in signal jets can be estimated by placing SE jets into mixed events and pairing with ME tracks

- **Removes uncorrelated particle contributions from Sig. jets**
Jet fragmentation functions – Results

Jet shapes and FFs in STAR – Joel Mazer

Au+Au, $\sqrt{s_{NN}} = 200$ GeV, 40-60% centrality class and three $p_{T,jet}$ ranges

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

- Fragmentation function prior variations in unfolding are not included in the systematic uncertainties

PYTHIA 8 Monash 2013 tune: consistent with data, tuned to LHC, and needs further parameter tuning at RHIC energies

- STAR PYTHIA6 tune: see Nihar Sahoo’s talk (#238, 6/2 12:20 ET) for comparison
40-60% central Au+Au / p+p (PYTHIA) ratio at 200 GeV:
- Remains near 1 within uncertainties throughout the full z range and for 3 separate charged jet $p_T$ ranges spanning **15-30 GeV/c**
Jet fragmentation functions – Results

- 40-60% central Au+Au / p+p (PYTHIA) ratio at 200 GeV:
  - Remains near 1 within uncertainties throughout the full z range and for 3 separate charged jet $p_T$ ranges spanning 15-30 GeV/c

- These results can potentially be connected to various physics scenarios:
  - Tangential jet selection with a high-$p_T$ trigger particle and recoil jet configuration?
  - Short path-length of jets in medium in 40-60% centrality?
  - Little jet-medium interactions in 40-60% centrality at 200 GeV?
Jet shapes

- Less steep at 200 GeV than LHC energies (with variations in kinematics and jet selection)
- **EP-dependent**: low-$p_T$ tracks have larger yields and pushed toward farther distances in the out-of-plane direction → sensitivity on path length dependence of jet quenching
- Results for $p+p$ & different jet types are on their way

Jet fragmentation functions

- Charged recoil jets with respect to a high-momentum trigger particle studied
- 40-60% Au+Au/PYTHIA at 200 GeV remains near 1 over full $z$ within uncertainties for 15-30 GeV/$c$ jets
  - PYTHIA 8 needs further tuning at RHIC energies
- Results for central & $p+p$ are on their way
Backup slides
Jet shapes – Event-plane dependence

Equilibration in medium
Fewer jets, lower high-\(p_T\) yield out of plane

Bremsstrahlung
Softer, higher yield out of plane

Fluctuations
Individual jets' energy loss may vary
Jet fragmentation functions @ 5.02 TeV


Figure 15: Ratios of $D(z)$ distributions in six centrality intervals of Pb+Pb collisions to $pp$ collisions evaluated in four $p_T$ 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 $p_T$ increases from left to right panels.

Figure 16: Ratios of $D(p_T)$ distributions in six centrality intervals of Pb+Pb collisions to $pp$ collisions evaluated in four $p_T$ 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 $p_T$ increases from left to right panels.
Jet shapes @ 2.76 TeV

Analyses details

In the presented measurements:
- 2014, Au+Au collisions at \( \sqrt{s_{NN}} = 200 \text{ GeV} \)
- Minimum-bias + high-tower triggered events
- Anti-\( k_T \) algorithm for jet reconstruction with \( R = 0.4 \) and \( |\eta_{\text{jet}}| < 1.0 - R \)
- In the jet shape measurement:
  - HardCore \( p_{T,\text{jet}} \) is estimated without a \( \rho A \) subtraction
  - Mixed event class is defined with centrality, \( z_{\text{vtx}} \), and \( \Psi_{\text{EP}} \) bins. There are 15 \( z_{\text{vtx}} \) bins, 4 \( \Psi_{\text{EP}} \) bins, and 16 centrality bins
- 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 \( z_{\text{vtx}} \), \( \Psi_{\text{EP}} \) track multiplicity bins. There are 15 \( z_{\text{vtx}} \) bins, 4 \( \Psi_{\text{EP}} \) bins, and 8 multiplicity bins
  - In fragmentation function unfolding, detector effects are simulated with Fast Simulation (efficiency and momentum resolution)
Little/no path length dependence

- Path length dependence naively predicted by every model
- No path length dependence seen in reaction plane dependent $A_j$ either
- Insufficient sensitivity?

Statistical variation in energy loss is more important than path length dependence