Recent Results on Jet Physics from STAR

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Introduction

- Jets and high-$p_T$ particles from hard scattering in heavy-ion collisions can probe the QGP
- The first experimental evidence of “jet quenching” from STAR

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**Most recent results on jet physics from STAR**

- Di-jet imbalance
- Event-plane dependent measurements
- Semi-inclusive jet (triggered-jet)
- Jet flavor dependence
- Jet angular scale dependence

Various measurements can be connected to different aspects of jet properties
Key Questions for more derivative jet-quenching observables

- Dependence on where the jet is produced inside of the medium?
- Path-length dependence in non-central collisions?
- Flavor dependence?
- Jet angular scale dependence?
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Di-jet imbalance from two situations?
Introduction

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The Solenoidal Tracker At RHIC (STAR)

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

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

**Neutral constituents**

**Charged constituents**

**Charged Jet**
Di-jet Imbalance
Di-jet Imbalance

- \[ A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}} \]

- **Hard-core jet vs. Matched jet**

**For** \( R = 0.4 \) **hard-core jet, more di-jet momentum imbalance compared to** \( p+p \)**

- Balance recovered when soft constituents are included (matched-jet)

- **For** \( R = 0.2 \), **balance no longer recovered** in matched-jet

- ✓ **Softening** of jet constituents and **Broadening** of the jet structure
Di-jet Imbalance

- $A_J = \frac{p_T^{Lead} - p_T^{SubLead}}{p_T^{Lead} + p_T^{SubLead}}$

- **Hard-core jet VS. Matched jet**

  - Constituent $p_T^{Cut} = 2$ GeV/c
  - Reduce BG and combinatorial jets

- **Constituent $p_T^{Cut} = 0.2$ GeV/c**
  - Geometrically matched to the hard-core jet

  - Balance recovered when soft constituents are included (matched jet)
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Di-jet Imbalance

- Varying the jet definition ($R$, constituent $p_T$ cut, ...) effectively controls the path length of jets in the medium (Jet Geometry Engineering).

- Matched jet with various hard-core constituent $p_T$ cut and $R$
  - Imbalance at small $R$
  - Balance ONLY restored with increased $R$ (~0.35) when soft particles are included.
Di-jet Imbalance

- Varying the jet definition ($R$, constituent $p_T$ cut, ...) effectively controls the path length of jets in the medium (Jet Geometry Engineering)

Jet Geometry Engineering Works!
More differential measurements with the help of increase in statistics with recent RHIC runs

Centrality dependence of $A_j$ – More balanced in peripheral Au+Au collisions
Event-plane Dependent Measurements

Out-of-plane vs. In-plane
Event-plane Dependent Jet-hadron Correlations

- Previous jet-hadron correlations by STAR (Phys. Rev. Lett. 112 (2014) 122301)
  - Suppression of high-$p_T$ associated particle yield is balanced by low $p_T$ associated particle enhancement

- More differential measurement using the trigger jet angle with respect to the event plane
  - In-plane, mid-plane, and out-of-plane

\[
\frac{(1/N_{\text{trig}})d(N_{\text{unc}})}{d\Delta\phi} = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{unc}}}{d\Delta\phi} 
\]

In-plane
\[1.0 < p_T^{assoc} < 1.5 \text{ GeV/c} \quad |\Delta\phi| < 0.6\]

Mid-plane
\[\text{Au-Au } \sqrt{s_{NN}} = 200 \text{ GeV, 20-50\% } \text{Anti-}k_T \text{ full jets, } R=0.4 \]
\[p_T^{\text{chrem, jet}} = 15-20 \text{ GeV/c}\]

Out-of-plane
\[p_T^{\text{chc}, E_T^{\text{clus}} > 2.0 \text{ GeV}} \]
\[p_T^{\text{lead const}, > 4.0 \text{ GeV}} \]

All combined angles

STAR Preliminary

Correlated unc.
Background unc.

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Event-plane Dependent Jet-hadron Correlations

- No significant event plane dependence is observed within uncertainties

STAR Preliminary

Near-side yield

Away-side yield

Near-side width

Away-side width
Event-plane Dependent Jet-hadron Correlations

- No significant event plane dependence is observed within uncertainties

Consistent with LHC results

Near-side yield

- Pb-Pb $s_{NN} = 2.76$ TeV, 30-50% centrality
- Anti-$k_T$ full jets, $R=0.2$
- $p_T^{ch+ne}$ = 20-40 GeV/c
- $p_T^{ch, E_t^{clus}} > 3.0$ GeV
- $E_{T, lead ~clus} > 6.0$ GeV

Away-side yield

- Pb-Pb $s_{NN} = 2.76$ TeV, 30-50% centrality
- Anti-$k_T$ full jets, $R=0.2$
- $p_T^{ch+ne}$ = 20-40 GeV/c
- $p_T^{ch, E_t^{clus}} > 3.0$ GeV
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ALICE Preliminary

$|\Delta n| < 0.6$

NS yield range: $-1.047 < \Delta \phi < 1.047$

points displaced for visibility

Scale uncertainty 6%

STAR Preliminary

$|\Delta n| < 0.6$

NS width range: $-\pi/3 < \Delta \phi < \pi/3$

points displaced for visibility

ALICE Preliminary

$|\Delta n| < 0.6$

AS yield range: $2.094 < \Delta \phi < 4.189$

points displaced for visibility

Scale uncertainty 6%

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Event-plane Dependent Di-hadron Correlations – Recoil Width

- After selecting events with high recoil momentum within $0.5 < \eta < 1.0$, two-particle correlation functions in close-region and far-region, separately

- Under the assumption that the flow contribution is equal in two regions, the difference between close-region and far-region correlation functions provides information on away-side width of jet-like correlations without the flow contribution.
Depending on the trigger particle angle with respect to the event plane ($= \phi_s$), the difference of two-particle correlation functions shows different away-side widths ($= \sigma$) after correcting for the EP resolution.

Larger width for out-of-plane triggers – indication of jet-medium interactions.
Event-plane Dependent Di-hadron Correlations with ESE

- Previous event-plane (EP) dependent di-hadron correlations
  ✓ Implication of path-length dependence of energy loss in the medium (shorter path-length for in-plane trigger and longer path-length for out-of-plane trigger)

\[ \phi_s = 0^\circ - 15^\circ \]

\[ \phi_s = 15^\circ - 30^\circ \]

\[ \phi_s = 30^\circ - 45^\circ \]

\[ \phi_s = 45^\circ - 60^\circ \]

\[ \phi_s = 60^\circ - 75^\circ \]

\[ \phi_s = 75^\circ - 90^\circ \]

\[ \Delta \phi = \phi - \phi_t \text{ [rad]} \]

\[ \frac{(1/N_{\text{trig}}) dN/d\Delta \phi}{0} \]

\[ \frac{0.3}{0} \]

\[ \frac{0.2}{0} \]

\[ \frac{0.1}{0} \]

\[ 0 \]

\[ 0 \]

\[ \text{Au+Au 200 GeV, 20-60%, } 3<p_T<4 \text{ GeV/c, } 1<p_T<2 \text{ GeV/c, } \vert n \vert<1 \]

\[ \text{STAR, Phys. Rev. C 89 (2014) 041901} \]

- Event shape engineering (ESE) can further control the initial geometry with the fixed average energy density – Measurements in small-\(q_2\) and large-\(q_2\) events separately

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Event-plane Dependent Di-hadron Correlations with ESE

- Polar representation of two-particle angular correlations
- **Near-side** – Higher peak in large-$q_2$ events with **in-plane** trigger
- **Away-side**
  - Larger associated particle yields toward in-plane direction
  - Higher peak in large-$q_2$ events with **in-plane** trigger
  - Consistent with path-length dependent picture?
Semi-inclusive Spectra
h-Triggered Recoil Jets

- Fully corrected $h^{\pm}$-triggered charged recoil jet
  - Strong suppression via $I_{CP}$
  - Medium-induced broadening 

Comparison between $R = 0.2$ and $R = 0.5$
• $\gamma_{\text{dir}}$+jet and $\pi^{0}$+jet
  ✓ Path length
  ✓ Color factor
  ✓ Parton energy

• Similar level of suppression observed
Jet Flavor Dependence

c-jet vs. gluon-jet
D⁰-hadron Correlations

- Heavy Flavor Tracker (HFT) provides significantly better identification of heavy-flavor particles

- D⁰-hadron two-particle angular correlations with D⁰ → π±K∓ channel

Au+Au, √s_{NN} = 200 GeV, D⁰ p_T = 2–10 GeV/c, h± p_T > 0.15 GeV/c

STAR Preliminary

0-20%

20-50%

50-80%
D⁰-hadron Correlations

- Similar width and yield results to light-flavor correlations – Indication of similar behavior of correlations between light-flavor and c
Heavy-flavor jet tagging performance in $p+p$ with low-level tagging algorithms

- Possibility of future heavy-flavor tagged jet analysis in STAR with HFT
Jet Angular Scale Dependence

Narrow jet vs. Wide jet
Jet Angular Scale Dependence

• Interaction of the jet with medium could depend on the jet’s angular scale
  Majumder, A and Putschke, J Phys Rev C 93 054909
  Mehtar Tani, Y and Tywoniuk, K arXiv:1707.07361

• Clustering all constituents into smaller radius jets ($R = 0.1$) → leading and subleading subjets

• $\theta_{SJ} = \Delta R($Leading$SJ$ axis, Subleading$SJ$ axis$)$
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Jet Angular Scale Dependence

$$\theta_{SJ} = \Delta R(\text{Leading SJ axis, Subleading SJ axis})$$

• $A_J$ measurements for hard-core and matched jets with different $\theta_{SJ}$ selections

• No significant difference between different $\theta_{SJ}$ selections
Summary

- Various jet measurements are on-going in STAR
- Di-jet imbalance for hard-core di-jets
  - Balance recovered with soft particles within $R = 0.4$
  - More differential measurements (Centrality, jet reconstruction parameter)
- Event-plane dependent measurements
  - Indication of jet-medium interaction + path-length dependence
- Semi-inclusive measurements ($h+\text{jet}$, $g+\text{jet}$) and $D^0$-hadron measurements
  - Little flavor dependence of jet-quenching
- Jet angular scale dependent $A_J$ - No significant dependence

Stay tuned for upcoming Jet Results/Publications from STAR!
Backup
Jet Geometry Engineering at RHIC

• Steeply falling $p_T$ spectrum at RHIC – good correlation between jet and parton energies

Leading trigger
✓ Jet+hadron correlation
✓ h+jet spectra

Di-jet imbalance

2+1 correlations

• Surface bias from trigger selection, particularly at RHIC energies, enables to use jet definition ($R$, constituent $p_T$ cut, ...) to select jet production vertex and di-jet origentation
Event selection with high recoil momentum within $0.5 < \eta < 1.0$

\[ P_X|_{\eta_2} = \sum_{\eta_1 < \eta_a < \eta_2, |\phi_a - \phi_{\text{trig}}| > \frac{\pi}{2}} p_T^a \cos(\phi_a - \phi_{\text{trig}}) \frac{1}{\epsilon} \]

\( \epsilon \): single-particle acceptance efficiency

For each centrality, cut on 10% left tail of \( P_X \) distribution to enhance away-side jet population in \( (\eta_1, \eta_2) \) acceptance
Two-particle correlation functions are fitted with a model with 8 parameters:

$$A_0 + 2A_Q(2D)\cos(2\Delta\phi) + A_{NS}e^{\frac{1}{2\sigma_{NS,\Delta\eta}^2} + \frac{1}{2\sigma_{NS,\Delta\phi}^2}} + A_{AS}e^{\frac{1}{2\sigma_{AS,\Delta\eta}^2} + \frac{1}{2\sigma_{AS,\Delta\phi}^2}} + \text{periodicity for } \Delta\phi \text{ Gaussian}$$
SoftDrop $R_g$ vs. $\theta_{SJ}$

- SoftDrop $R_g$ is more sensitive to background fluctuations
Jet Angular Scale Dependence

$A_J = \frac{p_{T,\text{Trig}} - p_{T,\text{Recoil}}}{p_{T,\text{Trig}} + p_{T,\text{Recoil}}}$