Di-Jet Measurements with STAR

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Jets

theory: $X \rightarrow q\bar{q}$ (or $g$)

experiment: collimated shower of hadrons

theory $\leftrightarrow$ jet-finding $\leftrightarrow$ experiment

jets are calculable: pQCD

extremely good agreement over several orders of magnitude

FastJet


[arXiv:1506.06314]
Jet modification in the QGP

partonic energy loss

- gluon radiation (primary)
- collisional energy loss (small)

broadening and softening

Jet in vacuum

Jet quenching/glueon radiation

Jet in medium

Jet broadening

Suppression of high-$p_T$ particles

Enhancement of low-$p_T$ particles
Jet production at RHIC & LHC

orders of magnitude difference in jet production cross section

    trigger: high-\(p_T\) hadron, jet w/ constituent cut, etc

models predict that with the softer RHIC spectrum

    trigger → surface bias

however, at the higher LHC energies,

    trigger → no surface bias

Jet trigger bias

However, this bias can be useful - opportunity to use jet cuts to select jet production vertex and di-jet orientation.

leading trigger

di-jet triggers

jet+hadron correlations, hadron+jet spectra

di-jet imbalance, di-jet hadron correlations

2+1 correlations
Jet+hadron correlations

- **Enhancement** of recoil jet low-p\(_T\) constituents, broadening
- **Suppression** of recoil jet high-p\(_T\) constituents

*STAR, PRL 112, 122301 (2014)*

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Nick Elsey, RHIC AGS Users Meeting 2018, BNL
Jet+hadron correlations

clear signal of **softening** and **broadening** in recoil jet

ergy loss in high-\(p_T\) region balanced by low-\(p_T\) excess
Hadron+jet spectra

semi-inclusive hadron-triggered recoil jet spectra

use of novel mixed-event method to extend kinematic reach to low jet $p_T$

Hadron+jet spectra

yield of jets recoiling from high $p_T$ hadron

suppression of recoil jet in central collisions compared to peripheral

Hadron+jet spectra

\[ \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{jets}}}{dp_{T,\text{jet}}^\text{ch}} (\text{GeV/c})^{-1} \]

\[ (1/N_{\text{trig}}) \frac{d^2N_{\text{jets}}}{dp_{T,\text{jet}}^\text{ch}} (\text{GeV/c})^{-1} \]

Increasing R $\rightarrow$ Increasing $I_{CP}$ $\rightarrow$ Broadening

Hard core jets at STAR

in a heavy ion background

large background energy density
Hard core jets at STAR

in a heavy ion background

$p_T^{\text{const}}>2$ GeV/c cut removes almost all background

clear jet signal
Hard core jets at STAR

in a heavy ion background

\[ p_T^{\text{Cut}} = 2 \text{ GeV/c} \]
\[ p_T^{\text{Lead}} > 20 \text{ GeV/c} \]
\[ p_T^{\text{SubLead}} > 10 \text{ GeV/c} \]
\[ |\Delta \phi - \pi| < 0.4 \]
\[ \text{anti-kt R=0.4} \]

\[ p_T^{\text{const}} > 2 \text{ GeV/c cut} \]

removes almost all background

geometric matching

no combinatoric jets, recover all constituents
Di-jet asymmetry at STAR

hard core di-jets more imbalanced with respect to p+p

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

Di-jet asymmetry at STAR

hard core di-jets more imbalanced with respect to p+p when soft constituents are included: balance recovered to level of p+p reference with R=0.4

\[ A_J = \frac{p_{T,Lead} - p_{T,SubLead}}{p_{T,Lead} + p_{T,SubLead}} \]
hard core di-jets more imbalanced with respect to p+p when soft constituents are included: balance no longer restored to the level of p+p in R=0.2 broadening of jet from 0.2 to 0.4

$$A_J = \frac{p_{T,\text{Lead}} - p_{T,\text{SubLead}}}{p_{T,\text{Lead}} + p_{T,\text{SubLead}}}$$

**Equation:**

$$p_{T,\text{Cut}}>2 \text{ GeV/c}$$
- p+p HT \(\oplus\) Au+Au MB
- Au+Au HT

**Graph:**
Di-jet asymmetry at STAR

hard core di-jets more imbalanced with respect to p+p when soft constituents are included: balance no longer restored to the level of p+p in R=0.2

more differential

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

Di-jet hadron correlations

**Di-jet definition**

\[
\begin{align*}
\text{pt}^{\text{Cut}} & = 2 \text{ GeV/c} \\
\text{pt}^{\text{Lead}} & > 20 \text{ GeV/c} \\
\text{pt}^{\text{SubLead}} & > 10 \text{ GeV/c} \\
|\Delta \phi - \pi| & < 0.4 \\
\text{anti-k}_T \text{ R} & = 0.4
\end{align*}
\]

**Correlations**

\[
\begin{align*}
\Delta \eta & = \eta^{\text{jet}} - \eta^{\text{track}} \\
\Delta \phi & = \phi^{\text{jet}} - \phi^{\text{track}}
\end{align*}
\]

**Au+Au 0-20% central**

1.0 < p_T^{assoc} < 2.0 GeV/c

**Systematic uncertainties**

- Tracking efficiency (±5%)
- Relative jet energy scale
- Relative tracking efficiency (±7%)
- Relative tower energy scale (±2%)

**Jet-finding correlations & yields**

- Detector level

**STAR Preliminary**
Background subtraction in di-jet hadron correlations

fit with a constant+gaussian constant subtracted as background

use sideband subtraction to account for flow in underlying event
Correlations in $\Delta\eta$

Projection range

$|\Delta\phi| < 0.71$

Yield contained within jet radius $R=0.4$

STAR Preliminary

3.0 < $p_T^{assoc}$ < 4.0 GeV/c

$p+p$ eff. corrected to Au+Au 0-20%

|<0.71

trigger jet

recoil jet
Correlations in $\Delta \eta$

projection range

$|\Delta \phi| < 0.71$

eyield contained within jet radius $R=0.4$

$1.0 < p_{\text{ass}} < 2.0$ GeV/c
Jet constituent Yields

- yields consistent between $\Delta \phi$ & $\Delta \eta$
- yield contained within $R=0.4$ for all $p_T$, consistent with $A_J$
- trigger jet: unmodified
- "surface bias"
- recoil jet: hint of modification for $p_T^{assoc}<2.0$ GeV/c
Consistent with $A_J$?

- minimal modification at high $p_T$ for both trigger & recoil jets
- possible enhancement at low $p_T$ in recoil jet

$A_J$ enhances sensitivity to modification

Why a small effect?

- effect is diluted in ensemble measurements like di-jet hadron correlations

More differential: select on $A_J$?

Soft-drop grooming

remove wide angle, soft radiation

Based on declustering an angular-ordered tree

\[ z > z_{\text{cut}} \theta^\beta \]

Soft Drop Condition:

Many applications, such as:
groomed energy, groomed radius
pp, jet mass, ...

Focus here (with \( \beta = 0 \)):

"Groomed Momentum Sharing"

\[ z_g = \frac{\min(pT_1, pT_2)}{pT_1 + pT_2} \]

\( p_T \) fraction carried by less-energetic sub-jet after grooming
Jet shape - $Z_g$

good agreement between p+p and Pythia

but is there measurable modification in the hard core di-jets?

$$Z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

STAR Preliminary
Jet shape - $z_g$

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

compare recoil jets in central Au+Au and p+p

no modification of $z_g$ for hard core selected recoil (and trigger) jets
Differential di-jet asymmetry

STAR Run 14 $\rightarrow$ 20x increase in di-jet pairs allows for differential $A_J$ measurement

**Goals**

centrality dependence of $A_J$

scan parameter space $(R, p_{T}^{Lead}, p_{T}^{Sub}, p_{T}^{Const})$

$\rightarrow$ “jet geometry engineering”
Summary

“softening” \((p_T < 2 \text{ GeV})\) & broadening beyond \(R=0.4\)

modified hard core di-jet pairs (softening & broadening)
energy recovered in narrow cone \((R=0.4)\)
no modification seen in \(z_g\); indicates split/shower outside medium (formation time)

Qualitatively consistent picture of partonic energy loss emerging at RHIC. Observed difference in broadening of jet structure can be related to in-medium path length/amount of diffusion of medium induced soft gluon radiation (enhancement at fixed \(p_T < 2 \text{ GeV}\)) in the QGP.
Future

new, large dataset

differential measurements

scan from minimally to maximally modified jets, connect biased and unbiased measurements

strongly constrain energy loss models

STAR Preliminary

Run 14 Au+Au
Run 7 Au+Au

0-20% Centrality

\[ p_{T}^{\text{const}} > 2.0 \text{ GeV/c} \]
\[ p_{T}^{\text{lead}} > 20.0 \text{ GeV/c} \]
\[ p_{T}^{\text{sublead}} > 10.0 \text{ GeV/c} \]
Thank you :)}
Hadron+jet - differing $R$

$Au+Au, \sqrt{s_{NN}}=200$ GeV

$9.0 < p_{T,\text{trig}}^{ch} < 30.0$ GeV/$c$

$A_{jet} > 0.05$, $R = 0.2$

anti-$k_T$

$STAR, \text{Phys.Rev. C96, 024905 (2017)}$
Hadron+jet - event mixing

these events only carry information about background fluctuations, and can be used to estimate background contribution to jet distribution

Schmah, Symposium on Jet & Electromagnetic Tomography of Dense Matter, 2015
Di-jet imbalance & effect of background

can background fluctuations balance jets to p+p level?

$A_J$ calculated with random eta cone, balance not recovered to p+p level

*STAR Collaboration, Phys. Rev. Lett. 119, 062301 (2017)*
Correlations in $\Delta \phi$

$3.0 < p_{\text{assoc}}^{T} < 4.0$ GeV/c

Star Preliminary

3.0 < $p_{\text{assoc}}^{T}$ < 4.0 GeV/c

*p+p HT* corrected to Au+Au 0-20% $|\Delta \eta| < 0.45$

trigger jet

recoil jet

projection range $|\Delta \eta| < 0.45$

yield contained within jet radius R=0.4

similar to $\Delta \eta$

~ circular jets

Nick Elsey, DNP Meeting Oct 2017, Pittsburgh
Correlations in $\Delta \phi$

- Projection range $|\Delta \eta| < 0.45$
- Yield contained within jet radius $R=0.4$
- Similar to $\Delta \eta$
  ~ circular jets

$1.0 < p_T^{assoc} < 2.0$ GeV/c
Further $z_g$ results

no significant modification of hard core selected trigger jets in Au+Au
**Z_g and Formation Time**

Vacuum and medium formation times

Hard medium-induced radiation happens late in the shower

\[
\tau_f^{\text{vac}} = \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}
\]

\[
\tau_f^{\text{med}} = \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}}
\]

At RHIC can only see medium for rare large angle emissions or even splittings. Larger \(z_{\text{cut}}\) and/or \(\Delta R_{12}\) selection would increase sensitivity.

Slide taken from M. Verweij, QM 2017
Conclusions

- Qualitatively consistent picture of energy loss measured in jet+hadron, hadron+jet, di-jet imbalance.
- Yield enhancement at low $p_T$, suppression at high $p_T$ in hard core di-jets, no significant broadening or modification in $z_g$.

Towards the future:
- Differential selection of jets based on geometry.
- Directly measure attenuation.
- Strongly constrain energy loss models.
- Systematically connect our biased and unbiased measurements.