Systematic studies of di-jet imbalance measurements at STAR

- Jet geometry engineering -

Nick Elsey for the STAR Collaboration
Wayne State University
Jet quenching in a nutshell

- Partonic energy loss
- Gluon radiation (primary)
- Collisional energy loss (small)

Jet in vacuum

Jet in medium

Jet quenching/glueon radiation

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 (Renk, Zapp,...) predict that with the softer **RHIC** spectrum

**trigger** → surface bias

however, at the higher **LHC** energies,

**trigger** → no surface bias

Jet trigger bias

this bias can be helpful - opportunity to use jet definition ($R, p_T^{\text{const}}$) to select jet production vertex and di-jet orientation - jet geometry engineering

jet+hadron correlations, hadron+jet spectra

STAR, PRL 112, 122301 (2014)
STAR, PRC 96, 024905 (2017)

di-jet imbalance, di-jet hadron correlations

2+1 correlations
STAR, PRC 83 061901 (2011)
STAR, PRC 87 44903 (2013)
Hard core jets at STAR

in a heavy-ion collision

large background energy density
Hard core jets at STAR in a heavy-ion collision

\[ p_T^{\text{hard \ const}} > 2 \text{ GeV/c cut} \quad \rightarrow \quad \text{removes almost all background} \]
Hard core jets at STAR

in a heavy-ion collision

$\mathbf{p_T^{hard\; const}} > 2 \text{ GeV/c}$
$\mathbf{p_T^{lead}} > 20 \text{ GeV/c}$
$\mathbf{p_T^{subLead}} > 10 \text{ GeV/c}$
$|\Delta\phi - \pi| < 0.4$
anti-kt $R=0.4$

removes almost all background
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

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


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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 $R=0.2$

broadening of jet from 0.2 to 0.4 softening of jet constituents

\[ A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}} \]
Di-jet asymmetry at STAR

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

$A_J$ is insensitive to the details of which jet is modified

di-jet hadron correlations

Di-jet hadron correlations

di-jet definition

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

correlations

\[ \Delta \eta = \eta^{\text{jet}} - \eta^{\text{track}} \]
\[ \Delta \phi = \phi^{\text{jet}} - \phi^{\text{track}} \]

trigger jet: require EMCal hit w/ \( E_T > 5.4 \) GeV

recoil jet: back-to-back with trigger jet

Au+Au 0-20% central

\[ 1.0 < p_T^{\text{assoc}} < 2.0 \text{ GeV/c} \]

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![Histogram](Image)

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Correlated jet yield

yields consistent between
\( \Delta \phi \) \& \( \Delta \eta \)

yield contained within \( R=0.4 \)
for all \( p_T \), consistent with \( A_J \)

trigger jet: \( p+p \) like
"surface bias"

recoil jet: hint of modification
enhancement in yield
for \( p_T^{\text{assoc}}<2.0 \text{ GeV}/c \)

for this \( p_T^{\text{hard const}} \) selection
( > 2.0 GeV/c), modification
appears to be mainly in recoil jet
Jet geometry engineering

we have a set of jets with specific kinematics that we understand well

can varying the jet definition select more or less modified jets?

modification —> path length
Quantifying modification

vary the jet definition

\[ \text{jet } p_T \]

\[ \text{hard constituent } p_T \text{ cut} \]

\[ \text{jet radius } R \]

use hard core and matched \( A_J \) as our observables

compare \( \text{Au+Au} \) to \( \text{p+p} \) embedded using a binned two-sample Kolmogorov-Smirnov (K-S) test

\( p\text{-value} \) = probability that data came from same probability distribution
Differential di-jet imbalance

hard core di-jets for R=0.4, scan $p_T^{\text{hard const}}$

$R = 0.4$

$p_T^{\text{hard const}} > 1 \text{ GeV}/c$

0-20% central

$p_T^{\text{lead}} > 16 \text{ GeV}/c$

$p_T^{\text{sublead}} > 8 \text{ GeV}/c$

anti-$k_T$ algorithm

K-S p-value $<< 1.0$
Differential di-jet imbalance

hard core di-jets for R=0.4, scan $p_T^{\text{hard const}}$

R = 0.4

$p_T^{\text{hard const}} > 1.5 \text{ GeV/c}$

0-20% central

$p_T^{\text{lead}} > 16 \text{ GeV/c}$

$p_T^{\text{sublead}} > 8 \text{ GeV/c}$

anti-$k_T$ algorithm

K-S p-value $<< 1.0$
Differential di-jet imbalance

hard core di-jets
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$
$p_T^{\text{hard const}} > 2.0 \text{ GeV/c}$

0-20% central
$p_T^{\text{lead}} > 16 \text{ GeV/c}$
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K-S p-value $<< 1.0$
Differential di-jet imbalance

hard core di-jets
for R=0.4, scan $p_T^{\text{hard const}}$

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0-20% central
$p_T^{\text{lead}} > 16 \text{ GeV/c}$
$p_T^{\text{sublead}} > 8 \text{ GeV/c}$
anti-$k_T$ algorithm

Now, we can repeat the procedure with the jet radius

K-S p-value $< 1.0$
Differential di-jet imbalance

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$\rho_{\text{const}} = 3$ fraction

$R = 0.35 \frac{A}{|A|}$

$|A|$

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Differential di-jet imbalance

hard core di-jets
modified for all kinematic selections

three distinct classes
using K-S test ($p = K-S$ p-value)

- balanced ($p > 0.01$)
- semi-balanced ($10^{-4} < p < 0.01$)
- imbalanced ($p < 10^{-4}$)
Differential di-jet imbalance

matched di-jets
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$
$p_T^{\text{hard const}} > 1 \text{ GeV/c}$
$p_T^{\text{match const}} > 0.2 \text{ GeV/c}$

0-20% central
$p_T^{\text{lead}} > 16 \text{ GeV/c}$
$p_T^{\text{sublead}} > 8 \text{ GeV/c}$
anti-$k_T$ algorithm

K-S p-value $<< 1.0$
Differential di-jet imbalance

matched di-jets
for $R=0.4$, scan $p_T^{\text{hard const}}$

$R = 0.4$

$p_T^{\text{hard const}} > 1.5 \text{ GeV/c}$

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0-20% central

$p_T^{\text{lead}} > 16 \text{ GeV/c}$

$p_T^{\text{sublead}} > 8 \text{ GeV/c}$

anti-$k_T$ algorithm

K-S p-value $= 0.0006$
Differential di-jet imbalance

matched di-jets
for R=0.4, scan $p_T^{\text{hard const}}$

\[ R = 0.4 \]
\[ p_T^{\text{hard const}} > 2.0 \text{ GeV/c} \]
\[ p_T^{\text{match const}} > 0.2 \text{ GeV/c} \]

0-20% central
\[ p_T^{\text{lead}} > 16 \text{ GeV/c} \]
\[ p_T^{\text{sublead}} > 8 \text{ GeV/c} \]
anti-$k_T$ algorithm

K-S p-value = 0.17
Differential di-jet imbalance

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p+p HT

0-20% central matched Au

p+p HT

matched const

0.25 > 0.2 GeV/c

Au+Au MB

J

0.05

0.1

0.15

0.2

0.25

0.3

0.35

0.4

jet radius

R=0.2 I A J

R=0.25 I A J

R=0.3 I A J

R=0.35 I A J

R=0.4 I A J

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Differential di-jet imbalance

**hard core di-jets**
modified for all kinematic selections

**matched di-jets**
reducing $p_T^{\text{hard const}}$
can increase modification beyond $R=0.4$

- balanced ($p > 0.01$)
- semi-balanced ($10^{-4} < p < 0.01$)
- imbalanced ($p < 10^{-4}$)

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Matched di-jets

- $p_T^{\text{hard const}}$ (GeV/c)
  - 1.0
  - 1.5
  - 2.0
  - 2.5
  - 3.0

- jet radius
  - 0.2
  - 0.25
  - 0.3
  - 0.35
  - 0.4
Estimate of the effect of background on balancing

- fluctuations in the background density can shift the $A_J$ distribution

- estimate the sensitivity of our measurement to correlated signal yield by embedding hard-core jets into random MB events

- quantify sensitivity using K-S test to evaluate the difference between Au+Au and Au+Au hard-core embedded in random MB events
Estimate of the effect of background on balancing

- fluctuations in the background density can shift the $A_J$ distribution
- estimate the sensitivity of our measurement to correlated signal yield by embedding hard-core jets into random MB events
- quantify sensitivity using K-S test to evaluate the difference between Au+Au and Au+Au hard-core embedded in random MB events
Differential di-jet imbalance

matched jets can get some “balance” from background fluctuations

compare matched jets to hard-core jets embedded in Au+Au MB

Estimate of sensitivity to physical balance

sensitive (p < 0.01)

insensitive (p > 0.01)
Radial scan of matched jets

at what radius does a set of imbalanced hard core jets (R=0.2) recover its energy?

fix hard-core jet at R = 0.2

scan through matched jet radii (R=0.2 → 0.4)
Radial scan of matched jets

at what radius does a set of imbalanced hard core jets (R=0.2) recover its energy?

start with a narrow hard core jet

scan through matched jet radii (R=0.2 -> 0.4) matched jet radius

0-20% central
\( p_{T}^{\text{lead}} > 16 \text{ GeV/c} \)
\( p_{T}^{\text{sublead}} > 8 \text{ GeV/c} \)
anti-\( k_T \) algorithm
Radial scan of matched jets

at what radius does a set of imbalanced hard core jets (R = 0.2) recover its energy?

- radial modification is relatively independent on $p_T^{\text{hard\ const}}$
- selecting narrower/harder/higher energy jets with $R = 0.2$

0-20% central
$p_T^{\text{lead}} > 16 \text{ GeV/c}$
$p_T^{\text{sublead}} > 8 \text{ GeV/c}$
anti-$k_T$ algorithm

Radial scan of matched jets

matched jet radius

$p_T^{\text{hard\ const}} (\text{GeV/c})$

0.2 0.25 0.3 0.35 0.4

matched jet radius
Moving forward

2014 Au+Au 200 GeV
20x increase in statistics

allow for wider jet kinematic range

centrality dependence

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\[ \text{fraction} \]

\[ A_j \]

Conclusions

- using hard core di-jets, we’ve measured energy loss, and we can define jet selections where we recover energy in our original cone - allows for calculation of fragmentation functions
- demonstrated jet geometry engineering, and the ability to control the extent of the energy loss using jet kinematic cuts

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 in the QGP.
Thank You
Kolmogorov-Smirnov two-sample test

- estimate the probability two data samples came from the same underlying distribution

- build the empirical distribution function (~CDF) for each dataset & find the maximal deviation between the two

- scale by an appropriate factor to generate a probability

\[
D_{n,m} = \sup_x |F_{1,n}(x) - F_{2,m}(x)|, \\
D_{n,m} > c(\alpha) \sqrt{\frac{n + m}{nm}}. \\
c(\alpha) = \sqrt{-\frac{1}{2} \ln\left(\frac{\alpha}{2}\right)}. \\
\]

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<td>1.73</td>
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Estimation of the effect of jet definition on jet kinematics in vacuum

- using pythia, estimate the average $p_T^{\hat{}}$ for each jet definition
- narrower, harder constituent cut jets on average come from higher energy processes
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)
Jet+hadron correlations

- Clear signal of **softening** and **broadening** in recoil jet energy 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