Di-Jet Imbalance Measurements and Semi-Inclusive Recoil Jet Distributions in Central Au+Au Collisions in STAR

Jörn Putschke
for the STAR Collaboration

(Wayne State University)
**Jet Quenching via triggered correlations at RHIC**

### Di-hadron

**STAR, PRL 97, 162301 (2006)**

### γ-hadron

**STAR, PRC 82, 034909 (2010)**

**PHENIX, PRL 111, 032301 (2013)**

### Jet-hadron

**STAR, PRL 112, 122301 (2014)**

**Different triggers → different biases**

**Observations:**
- high-z suppression
- low-z enhancement
- *modest* azimuthal broadening at low $p_T$

Jörn Putschke for the STAR Collaboration, QM14 Darmstadt
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Different triggers → different biases

Observations:
- high-z suppression
- low-z enhancement
- modest azimuthal broadening at low \( p_T \)

But recoil hadrons only probe jet structure statistically!

Next Chapter:
Reconstruction of recoil jets; again utilize different triggers and biases
Jets in STAR

Data sets:

(i) Run 7 Au+Au and Run 6 p+p
\[ \sqrt{s_{\text{NN}}} = 200 \text{ GeV}, \text{ High Tower (HT) Trigger} \]

\[ TPC+BEMC \text{ (charged+neutral)} \rightarrow \text{Di-Jet Imbalance } A_J \]

(ii) Run 11 Au+Au \[ \sqrt{s_{\text{NN}}} = 200 \text{ GeV Minimum Bias} \]
\[ TPC \text{ (charged only in this analysis)} \]
\[ \rightarrow \text{Recoil Jets} \]

Jet-Finding Algorithm:

Anti-\( k_T \) algorithm (R=0.2-0.4)

\[ M. \text{ Cacciari and G. Salam} \]
\[ \text{Phys. Lett. B 641, 57 (2006)} \]
$A_J$: (Biased) Di-Jet Selection and “Notation”

$p_{T, \text{cut}} = 2$ GeV/c
$p_{T, \text{Lead}} > 20$ GeV
$p_{T, \text{SubLead}} > 10$ GeV
$\Delta \Phi_{\text{Lead,SubLead}} > \frac{2}{3} \pi$

Calculate $A_J$ with constituent $p_{T, \text{cut}} > 2$ GeV/c

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$$p_T = p_T^{rec} - \rho \times A$$
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**Calculate** \( A_J \) **with constituent** \( p_{T,\text{cut}} > 2 \text{ GeV/c} \)

\[
A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \quad p_T = p_{T}^{rec} - \rho \times A
\]

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**Calculate “matched”** \(|A_J| \) **with constituent** \( p_{T,\text{cut}} > 0.2 \text{ GeV/c} \).
Di-Jet Imbalance $A_J$ Au+Au 0-20% $R=0.4$

Anti-$k_T$ $R=0.4$, $p_{T,1}>20$ GeV & $p_{T,2}>10$ GeV with $p_T^{\text{cut}}>2$ GeV/c

Event Fraction

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

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Di-Jet Imbalance $A_J$ Au+Au 0-20% $R=0.4$

$\text{Anti-}k_T \ R=0.4, \ p_{T,1}>20 \text{ GeV} \ & \ p_{T,2}>10 \text{ GeV} \ \text{with} \ p_{T}^{\text{cut}}>2 \text{ GeV/c}$

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Au+Au di-jets more imbalanced than p+p for $p_T^{\text{cut}}>2$ GeV/c

$p$-value $<10^{-5}$ (stat. error only)
Di-Jet Imbalance $A_J$ Au+Au 0-20% $R=0.4$

Anti-$k_T$ $R=0.4$, $p_{T,1}>20$ GeV & $p_{T,2}>10$ GeV with $p_T^{\text{cut}}>2$ GeV/c

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Au+Au di-jets more imbalanced than p+p for $p_T^{\text{cut}}>2$ GeV/c

Au+Au $A_J \sim p+p$ $A_J$ for matched di-jets ($R=0.4$)
**Null-Hypothesis**

**Assumption:** Observed di-jet balancing for matched jets is **only** due to background fluctuations, **not** due to correlated signal yield!

**Method 1: Random Cone (RC):**

Take di-jet pair $p_T^{\text{Cut}} > 2 \text{ GeV/c}$ (w/o low $p_T$)

- $p_{T,\text{cut}} = 2 \text{ GeV/c}$
- $p_{T,\text{Lead}} > 20 \text{ GeV}$
- $p_{T,\text{SubLead}} > 10 \text{ GeV}$

Embed randomly the 2 Jet vectors into a Au+Au 0-20% Minimum Bias event

Calculate $|A_J|$ with $p_T^{\text{Cut}} > 0.2 \text{ GeV/c}$ using cone of R
**Null-Hypothesis**

**Assumption:** Observed di-jet balancing for matched jets is *only* due to background fluctuations, *not* due to correlated signal yield!

**Method 1: Random Cone (RC):**
Take di-jet pair $p_T^{\text{cut}} > 2$ GeV/c (w/o low $p_T$)

- $p_T^{\text{cut}} = 2$ GeV/c
- $p_T^{\text{Lead}} > 20$ GeV
- $p_T^{\text{SubLead}} > 10$ GeV

**Method 2: EtaCone (EC):**
Take di-jet pair $p_T^{\text{cut}} > 2$ GeV/c (w/o low $p_T$)

- Embed randomly the 2 Jet vectors into a Au+Au 0-20% Minimum Bias event
- Calculate $|A_J|$ with $p_T^{\text{cut}} > 0.2$ GeV/c using cone of $R$

- Embed the two Jet vectors into 0-20% Au+Au HT event $2*R$ away from reconstructed di-jet pair in that event
Null-Hypothesis

Anti-\(k_T\) R=0.4, \(p_{T,1}>20\) GeV & \(p_{T,2}>10\) GeV with \(p_T^{\text{cut}}>2\) GeV/c

Balancing of Au+Au matched di-jets due to correlated signal yield in a cone of R=0.4

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Method 1 (RC)

Method 2 (EC)
Select modified di-jet pairs with $p_T^{\text{cut}}>2 \text{ GeV/c}$ in Au+Au

→ quenched jet energy is recovered at low $p_T$ within a cone of $R=0.4$ – consistent with Jet-Hadron results
Anti-$k_T$ $R=0.2$, $p_{T,1} > 16$ GeV & $p_{T,2} > 8$ GeV with $p_{T}^{\text{cut}} > 2$ GeV/c

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

$p$-value<10^{-10}
(stat. error only)

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Di-Jet Imbalance $A_J$ Au+Au 0-20% $R=0.2$

$\text{Anti-}k_T \ R=0.2, \ p_{T,1}>16 \text{ GeV} \ & \ p_{T,2}>8 \text{ GeV with } p_T^{\text{cut}}>2 \text{ GeV/c}$

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Matched Au+Au $A_J \neq p+p A_J$ for $R=0.2$
$\rightarrow$ (recoil) Jet broadening in 0.2 – 0.4

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## Quick Summary of $A_J$ Measurements

<table>
<thead>
<tr>
<th></th>
<th>$R=0.4$</th>
<th>$R=0.2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Au+Au vs. p+p</strong></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>$p_T^{Cut}&gt;2$ GeV/c</td>
<td></td>
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<tr>
<td><strong>Matched</strong></td>
<td>O</td>
<td>X</td>
</tr>
<tr>
<td><strong>Au+Au vs. p+p</strong></td>
<td></td>
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<tr>
<td>($p_T^{Cut}&gt;0.2$ GeV/c)</td>
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</tbody>
</table>

**X** = "Non-identical" $A_J$ distribution (Au+Au vs. p+p)

**O** = "Identical" $A_J$ distribution (Au+Au vs. p+p)
Semi-inclusive Recoil Jets

**Charged hadron trigger:** $9 < p_T < 19$ GeV/c

**Charged particle jets:**
- Anti-$k_T$ $R=0.3$
- Constituent tracks: $p_T > 0.2$ GeV/c

Recoil jet azimuth: $|\phi - \pi| < \pi/4$

**Semi-inclusive Observable:**
Recoil jets per trigger

$$\frac{1}{N_{trig}^h} \frac{dN_{jet}}{dp_{T, jet}} = \frac{1}{\sigma^{AA \rightarrow h+jet+X}} \frac{d\sigma^{AA \rightarrow h+X}}{dp_{T, jet}}$$

**Ensemble-averaged analysis:**
- No rejection of jet candidates on a jet-by-jet basis
- Jet measurement is collinear-safe with low infrared cutoff (0.2 GeV/c)
Sample number of tracks from real event distribution in each centrality bin, $\Psi_{EP}$ bin and z-vertex bin

Pick one random track per real event → add to mixed event

Run jet-finder on mixed events ...
Excellent description of combinatorial jets background via new event mixing method!

→ Triggered Recoil jet distribution: SE-ME
Au+Au background subtracted distributions (SE-ME):

- **Ultimately**: Correct to particle level via unfolding of bkgd fluctuations and detector effects
- **Currently**: Compare to PYTHIA p+p distribution “smeared” by these effects

**Dominant sys uncertainty**: Tracking eff. → Jet energy scale (JES) uncertainty ~7%
Semi-inclusive Recoil Jets (SE-ME) $p_T^{\text{trig}}>9$ GeV/c

Au+Au background subtracted distributions (SE-ME):

- **Ultimately**: Correct to particle level via unfolding of bkgd fluctuations and detector effects
- **Currently**: Compare to PYTHIA p+p distribution “smeared” by these effects

Dominant sys uncertainty: Tracking eff. $\rightarrow$ Jet energy scale (JES) uncertainty $\sim 7\%$

---

**Peripheral Au+Au: Good agreement between data and PYTHIA**

**Central Au+Au: Strong suppression (relative to PYTHIA)**
First Look: Medium Induced Acoplanarity?

Charged Jets Au+Au 0-10%

Δφ

trigger hadron

Δφ

STAR Preliminary

Δφ

STAR Preliminary

Δφ

STAR Preliminary
Charged Jets Au+Au 0-10%

Δφ

trigger hadron

\[ 7.0 < p_x < 29.0 \text{ GeV/c} \]
\[ \sigma = 0.20 \pm 0.01 \]
STAR Data (60%-80%)

Preliminary (stat. errors only)

AuAu central vs peripheral: Similar widths; can measure large angle radiation
First Look: Medium Induced Acoplanarity?

Charged Jets Au+Au 0-10%

Δφ
trigger
hadron

RHIC vs LHC: Comparable widths

Preliminary (stat. errors only)

7.0<p_{T, A}^{jet}<29.0 GeV/c

σ = 0.20±0.01

STAR Data (60%-80%)

Δφ = \mid p_{T, A}^{jet} - p_{T, jet} \mid (rad)

AuAu central vs peripheral: Similar widths; can measure large angle radiation

RHIC vs LHC: Comparable widths

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Discussion: The Role of Biases


Biases ($p_T^{\text{Cut}}$, R, ...) can be used to change systematically the pathlength of the recoil jet (even more when also applied on recoil jet definition)

**Further advantage at RHIC:** Steeply falling spectrum at RHIC $\rightarrow$ good correlation to the initial parton energy
Discussion: The Role of Biases

Biases ($p_T^{\text{cut}}$, R, ...) can be used to change systematically the pathlength of the recoil jet (even more when also applied on recoil jet definition)

Further advantage at RHIC: Steeply falling spectrum at RHIC $\rightarrow$ good correlation to the initial parton energy

Di-Jet Imbalance $A_J$: Biased initial di-jet selection also on recoil jet ($p_T^{\text{cut}}>2$ GeV) $\rightarrow$ smaller pathlength/energy loss at later times $\rightarrow$ balance restored including low $p_T$ constituents for $R=0.4$ wrt $p+p$ (broadening observed within $R=0.4$; consistent with Jet-Hadron)
Discussion: The Role of *Biases*

*Biases* ($p_T^{\text{cut}}$, R, ...) can be used to change **systematically** the *pathlength* of the recoil jet

(even more when also applied on recoil jet definition)

**Further advantage at RHIC:** Steeply falling spectrum at RHIC $\rightarrow$ good correlation to the *initial parton energy*

**Di-Jet Imbalance $A_J$:**

Biased initial di-jet selection also on recoil jet ($p_T^{\text{cut}}>2$ GeV)
$\rightarrow$ smaller pathlength/energy loss at later times
$\rightarrow$ balance restored including low $p_T$ constituents for R=0.4 wrt p+p
(broadening observed within R=0.4; consistent with Jet-Hadron)

**Semi-inclusive Recoil Jets (h-Jet):**

No bias on recoil jet
$\rightarrow$ larger (maximized) pathlength for recoil jets
$\rightarrow$ more energy loss combined with jet broadening (Jet-Hadron)
$\rightarrow$ (strong) suppression wrt Pythia (R=0.3)

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Summary

New di-jet measurements from STAR:

\[ A_J \] : Balance restored for \( R=0.4 \) wrt \( p+p \) (for \textit{biased} di-jets)

\[ h-Jet \] : (Strong) suppression wrt Pythia (\( R=0.3 \));
    no evidence of large angle scattering

More data available (6x more HT triggered data wrt Run 7) and full jet analysis in Run 11.

Coherent Jet Quenching Program in STAR:

\textit{Statistically}: Di-Hadron, \( \gamma \)-Jet, Jet-Hadron and 2+1 Correlations

\textit{Extension via new/future jet Measurements:}

Explore systematically and differentially biases (\( p_T^{\text{cut}}, R, .. \)) in particular utilizing di-jet coincidence measurements at RHIC

→ engineer geometrical biases
→ “jet - tomography”
→ study evolution of soft gluon radiation
Backup
$\Delta A_J = A_J(p_T^{cut}>2\text{GeV}) - A_J(p_T^{cut}>0.2\text{GeV})$

Event Fraction

$\Delta A_J$ vs. $p_T$

$\Delta A_J$ larger for Au+Au than p+p

$\rightarrow$ more energy recovered at low $p_T$

Jörn Putschke for the STAR Collaboration, QM14 Darmstadt
$\Delta A_J = A_J(p_T^{\text{cut}} > 2\text{GeV}) - A_J(p_T^{\text{cut}} > 0.2\text{GeV})$

- $\Delta A_J$ larger for Au+Au than p+p $ightarrow$ more energy recovered at low $p_T$

R=0.2: $\Delta A_J$ Au+Au $\sim$ $\Delta A_J$ p+p $ightarrow$ similar energy recovered at low $p_T$
pp HT Reference and Systematic Errors

Reference:

pp HT \( \otimes \) AuAu MB

Embed pp HT randomly into AuAu 0-20% minimum bias event, adjusted for relative tracking efficiency between pp HT Y06 and AuAu HT Y07

Systematic Uncertainties (Analogous to Jet-Hadron Corr.)

- Tracking efficiency uncertainties 6%
- Relative Tower energy scale uncertainty 2%
- Background/vn: Null-Hypothesis Method1 vs. Method2
- Remaining uncertainties negligible

Reference:

STAR, PRL 112, 122301 (2014)
Systematic uncertainties of the h+jet distribution

Jet Energy Scale (JES) uncertainty: 7%
Dominant contribution: tracking efficiency
  • studied via embedding in Run11 data
  • average charged track reconstruction efficiency is about 68% at high $p_T$
  • the $p_T$-dependent efficiencies were varied by +/-10% (relative) and applied to the PYTHIA tracks as a systematic uncertainty on reference (instead of unfolding of data, TBD)

Track momentum resolution: negligible contribution to JES resolution (~1-2%)

Event plane correlations
No evidence of a correlation of high $p_T$ particles with the event plane
  (e.g.: STAR Phys.Rev.Lett. 93 (2004) 252301)
  → a bias of the jet spectrum due to event plane correlations with the trigger particle are unlikely.
  → an upper limit was estimated by using two different Delta $p_T$ distributions which were calculated in and out of plane.
Di-Jet Imbalance $A_J$ Au+Au 0-20% R=0.2 (I)

Anti-$k_T$ R=0.2, $p_{T,1}$>16 GeV & $p_{T,2}$>8 GeV with $p_T^{\text{cut}}>2$ GeV/c

Sys. Uncertainties:
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Anti-k_T R=0.2, p_T,1>16 GeV & p_T,2>8 GeV with p_T^\text{cut}>2 GeV/c

Sys. Uncertainties:
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Di-Jet Imbalance $A_J$ AuAu 0-20% R=0.2 (II)

Anti-$k_T$ R=0.2, $p_T,1>20$ GeV & $p_T,2>10$ GeV with $p_T^{cut}>2$ GeV

Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

Preliminary Event Fraction

$|A_J|$
AuAu Embedding: $p_T^{\text{Cut}}>2$ GeV

Anti-$k_T$ $R=0.4$, $p_{T,1}>20$ GeV & $p_{T,2}>10$ GeV with $p_T^{\text{cut}}>2$ GeV

Event Fraction

pp HT $\otimes$ AuAu 0-20%
pp HT
pp HT & rel. track eff.

Preliminary (Support) (stat. errors only)
AuAu Embedding: Matched jets with $p_T^{cut} > 0.2$ GeV

Anti-$k_T$ $R=0.4$, $p_{T,1} > 20$ GeV & $p_{T,2} > 10$ GeV with $p_T^{cut} > 2$ GeV

pp HT matched $\otimes$ AuAu 0-20%
pp HT matched
pp HT matched & rel. track eff.

Event Fraction

| $|A_{IJ}|$ |
|---|
| 0.7 |
| 0.6 |
| 0.5 |
| 0.4 |
| 0.3 |
| 0.2 |
| 0.1 |
| 0 |

Preliminary (Support) (stat. errors only)
PYTHIA8 Particle Level (PL) and Toy Bkg. Model

Event Fraction

Pythia8 PL
Pythia8 PL & Bkg
Pythia8 PL & Bkg (v2)
Pythia8 PL & Bkg & track eff. Y07
A_{J} at the LHC

Significant di-jet momentum imbalance $A_{J}$ observed in central Pb+Pb

Jörn Putschke for the STAR Collaboration, QM14 Darmstadt
The momentum difference in the di-jets is balanced by low $p_T$ particles at large angles relative to the away side jet axis.
The momentum difference in the di-jets is balanced by low $p_T$ particles at large angles relative to the away side jet axis

**LHC:**
Larger energy loss at early times
→ more diffusion in medium
→ larger angles
The momentum difference in the di-jets is balanced by low $p_T$ particles at large angles relative to the away side jet axis

**LHC:**
Larger energy loss at early times
→ more diffusion in medium
→ larger angles

**RHIC:**
Quenched energy closer to initial parton/jet direction. Can utilize biases for systematic exploration.
→ (easier) to study soft gluon radiation
Due to the steeply falling spectrum at RHIC, even with imposing biases ($p_T^{\text{cut}}$, ...), a good correlation to the initial parton energy is preserved.

Biases ($p_T^{\text{cut}}$, ...) can be used to change systematically the pathlength of the recoil jet.

Biases ($p_T^{\text{cut}}$, ...) can be further utilized to favor gluon recoil jets.