Studies of Jets through Correlations in Heavy Ion Collisions at RHIC

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"Erfahrung ist fast immer eine Parodie auf die Idee."
--Goethe
Introduction

- Why study jets in heavy ion collisions?
- Experimental method
- The near-side
- The away-side
- Where we go from here
Why study jets in heavy ion collisions?

- Hard parton scattering ⇒ back-to-back jets
  - Good (calibrated?) probe of the medium
- High multiplicity in A+A collisions
  - Individual jets cannot be reconstructed
  - Study jets via correlations of particles in space

• both azimuth and pseudorapidity

\[ \Lambda, \bar{\Lambda}, K^0, \Xi^+, \Xi^-, \ldots \]
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  - Study jets via correlations of particles in space

\[ \eta = -\ln(\tan(\theta/2)) \]

- both azimuth and pseudorapidity
**Motivation**

- Initial studies showed suppression of away-side peak in A+A collisions
  - \(2.0 \text{ GeV/c} < p_T^{\text{associated}}\)
- Inclusive \(p_T^{\text{associated}}\)
  - reappearance of away-side
  - more complex structure than d+Au, p+p
A caveat...

- Large background subtraction...
  - Signal/Background $\approx 0.05$
  - Depends on kinematic region
  - Signal/Background higher at higher $p_T$

J. Bielcikova QM06
Determination of yields and errors

Background:

\[ B(1+2 v_{\text{trig}}^2 v_{\text{assoc}}^2 \cos(2\Delta\Phi)) \]

\( v_2 \) – elliptic flow

Different fit methods for determination of \( B \)

- Assume there is no yield correlated with the jet at some point
- Zero Yield At Minimum (ZYAM)
- Zero Yield At 1 (ZYA1)

\( v_2 \) error \( \Rightarrow \) systematic error on correlations assuming ZYAM is correct
Assumptions in background subtraction

- The only correlated background is elliptic flow
- Elliptic flow is independent of jets and therefore the correlations can be separated into two independent components
- There is a point in azimuth where none of the correlations are due to jets

Any conclusions are heavily dependent on the validity of these assumptions!
• Primary Detectors: Drift chambers, time expansion chambers, pad chambers, vertex detector

• Azimuthal coverage: Two sections of $0<\varphi<\pi/2$

• Pseudorapidity coverage: $-0.35<\eta<0.35$
- Primary Detector: TPC
- Full azimuthal coverage: $0 < \varphi < 2\pi$
- Pseudorapidity coverage: $-1 < \eta < 1$
Near-side: Motivation

- Near-side shows modification
- Excess yield in Au+Au relative to p+p
Near-side: Motivation

- Long-range pseudorapidity ($\Delta \eta$) correlations observed by STAR in Au+Au at intermediate $p_T$
- Near side jet peak sits on plateau (Ridge)
  - Significant contribution to the near-side yield in central Au+Au
  - Some mechanisms for production call for flow

No $v_2$ subtraction – signal visible above $v_2$
Near-side: Ridge production mechanisms

- Parton radiates energy before fragmenting and couples to the longitudinal flow
  - gluon bremsstrahlung of hard-scattered parton
  - parton shifted to lower $p_T$
  - radiated gluon contributes to broadening

  - Recombination of thermal partons only indirectly affected by hard scattering, not part of the jet

Near-side: Method

- **Ridge** previously observed to be flat in $\Delta\eta$ in Au+Au

- To determine relative contributions, find yields for near-side, take $\Delta\Phi$ projections in
  - $-0.75 < \Delta\eta < 0.75$ \textbf{Jet + Ridge}
  - $0.75 < |\Delta\eta| < 1.75$ \textbf{Ridge}
  - \textbf{Jet} = (Jet + Ridge) – Ridge$^*.75/1.75$
  - \textbf{Ridge} = yield from $-1.75 < \Delta\eta < 1.75$ – Jet yield

- Flow contributions to jet cancel

- $v_2$ flat with $\eta$ for $|\eta|<1$

**Jet** yield per trigger increases with $p_T^{\text{trigger}}$

- Expected because higher $p_T^{\text{trigger}}$ should be "jettier"

**Ridge** yield shows weaker dependence on $p_T^{\text{trigger}}$

- **Ridge** dominant in central Au+Au

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Christine Nattrass  
Frankfurt, Jan. 7, 2007
Near-side: particle dependence

- Identified particles show similar yield trends to unidentified
- Particle ratios in Ridge closer to bulk than those in the Jet

J. Bielcikova, WWND07
Near-side Yield vs $N_{part}$  
Cu+Cu vs Au+Au

Identified triggers:

- **Jet yield**
  - Nearly flat with $N_{part}$ within errors across d+Au, Cu+Cu, Au+Au
  - No $v_2$ or background error due to method
  - No trigger dependence within errors

- **Ridge yield**
  - No Ridge within errors in d+Au
  - Rises with $N_{part}$ in Cu+Cu and Au+Au
  - No trigger dependence within errors

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3.0 GeV/c < $p_T^{\text{trigger}}$ 6.0 GeV/c; 1.5 GeV/c < $p_T^{\text{associated}}$ < $p_T^{\text{trigger}}$
C. Nattrass SQM07

Jet yield/trigger vs $N_{part}$

- Data points at same $N_{part}$ offset for visibility
- Jet yields: 10% error added to $V_0$ and $h$ triggers to account for track merging, 15% to $\Xi$ triggers

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Near-side Yield vs $N_{\text{part}}$  

$Cu+Cu$ vs $Au+Au$

Identified triggers:

- **Jet yield**
  - Nearly flat with $N_{\text{part}}$ within errors across $d+Au$, $Cu+Cu$, $Au+Au$
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- **Ridge yield**
  - No Ridge within errors in $d+Au$
  - Rises with $N_{\text{part}}$ in $Cu+Cu$ and $Au+Au$
  - No trigger dependence within errors
Near-side Yield vs \( N_{\text{part}} \) Cu+Cu vs Au+Au

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Data points at same \( N_{\text{part}} \) offset for visibility

\[ \sqrt{s_{\text{NN}}}=200 \text{ GeV}, |\Delta\eta|<0.7 \]

\( \text{STAR preliminary} \)

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Frankfurt, Jan. 7, 2007
Near-side Yield vs $N_{\text{part}}$  

** identifiers triggers:**

- **Jet yield**
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Near-side Yield vs $N_{\text{part}}$  

**Cu+Cu vs Au+Au**

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  - Rises with $N_{\text{part}}$ in Cu+Cu and Au+Au
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Near-side: Ridge

- Spectra of particles in Jet harder than those of particles in the Ridge
- Particles in Ridge similar to bulk
Near-side: Summary

• Enhanced yield in Au+Au collisions relative to p+p
• Extra yield is in Ridge
• Particles in Ridge closer to those in the bulk than those in the Jet
  – Particle ratios
  – Spectra
• Consistent with $N_{\text{part}}$ dependence on Ridge size
• Predictions which might distinguish mechanisms not quantitative enough to make detailed comparisons to theory
Away-side

- Shape change on away-side
- Excess yield at low $p_T$ on away-side

STAR PRL 95 (2005) 152301
Motivation: Away-side

- STAR and PHENIX: qualitative agreement
- STAR: dependent on systematic errors
  - systematic errors from disagreement of different methods of measuring $v_2$
- PHENIX: claim smaller systematic errors
  - systematic errors from one $v_2$ measurement (reaction plane)
Away-side: Motivation

PHENIX
Au+Au & p+p
$\sqrt{s} = 200$ GeV
arXiv:0705:3238

Whether we look at PHENIX results...
Away-side: Motivation

Or STAR results...

- Shape distortion increases with centrality
- Decreases with increasing $p_T^{\text{trigger}}$
- Degree of shape distortion dependent on $v_2$ subtraction
- Also see “punch through” of away-side at high $p_T^{\text{associated}}$

Centrality

60-80%
40-60%
20-40%
0-12%

6 < $p_T^{\text{trig}}$ < 10 GeV/c
Reminder: Background Subtraction


Before background subtraction

After background subtraction

Assumption that there is no yield at minimum

Signal sits on top of large background

No dip before background subtraction

Dip appears after background subtraction

1<p^\text{assoc}_T<2.5<p^\text{trigg}_T<4\text{GeV}/c

Au+Au 200 \text{ GeV} 0-5%
Away-side: Proposed models

• Where could this come from?
  – Large angle gluon radiation (Vitev and Polsa and Salgado).
  – Deflected jets, due to flow (Armesto, Salgado and Wiedemann) and/or path length dependent energy loss (Chiu and Hwa).
  – Hydrodynamic conical flow from Mach cone shock-waves (Stöcker, Casalderrey-Solanda, Shuryak and Teaney, Renk, Ruppert and Muller).
  – Cerenkov gluon radiation (Dremin, Koch).

• 2-particle correlations give the same qualitative results for all models \( \Rightarrow \) can't distinguish
Wisdom from Goethe

Da steh' ich nun, ich armer Tor,
Und bin so klug als wie zuvor!

Faust I
Goethe
3-particle correlations

- Two different coordinate systems
- Different background subtractions
- Both assume 2 components (jet + flow background)

STAR
Δφ-Δφ space (Δφ=φ-φ_{Trigger})

Ulery (STAR) QM’05

Ajitanand (PHENIX) HP06, IWCF’06

PHENIX
• polar coordinates
3-particle correlations: PHENIX

Au+Au 0-5 %

2.5 < p_T^{Trig} < 4 GeV/c
1 < p_T^{Assoc} < 2.5 GeV/c

Same Side
Away Side

Δφ*
θ*

Trigger

Near-side
Away-side

Ajitanand (PHENIX) HP06
3-particle correlations: PHENIX

Same Side

Δφ* θ*

Away Side

Normal jet simulations

Deflected jet simulations

Mach Cone simulations

40-60 %

10-20 %

0-5 %

huh?

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Frankfurt, Jan. 7, 2007
3-particle correlations: PHENIX

Ajitanand (PHENIX) HP06, IWCF’06

Δφ* Projections

\( v_2 \) subtracted

- Dependent on background subtraction
- Details of background subtraction not shown
- Central data not shown
3-particle correlations: STAR

- di-jets
- Conical Emission
- Deflected Jets
3-particle correlations: STAR

Subtracting a complicated background...

Still assuming ZYAM...

\[ v_4 = 1.15 v_2^2 \]
3-particle Correlations: STAR Results

Structure changes with centrality

Peripheral Au+Au looks like d+Au, p+p

Central Au+Au shows new features

Near-Near  Near-Away  Away-Away

1 < \textit{p}_{T}^{\text{associated}} < 2 \text{ GeV}/c, 3 < \textit{p}_{T}^{\text{trigger}} < 4 \text{ GeV}/c
3-particle Correlations: STAR Results

- On-diagonal and off-diagonal projections.
- Yellow bands are systematic errors.
- Significant off-diagonal peaks.

J. Ulery, ISMD07
3-particle Correlations: STAR Results

- Attempts at extracting emission angle
- No apparent $p_T$ dependence
- No apparent centrality dependence
3-particle Correlations: STAR Cumulant

- Clear mathematical definition
- Difficult to interpret
- Favors modification but the type of modification is unclear
3-particle Correlations: Summary

• Both STAR and PHENIX standard analyses slightly favor conical emission
  • STAR data slightly favors Mach cone over Cerenkov radiation
  • Both analyses dependent on validity of
    - ZYAM
    - 2 component picture
• Similar STAR analysis which does not support conical emission but has unclear interpretation
Another method - Baryon/Meson Ratio

- If there is a Mach cone, angle should depend on mass
- Error bars are still too large to conclude
- However, at least systematic errors for K\textsubscript{0}\text{S} and \Lambda are correlated

Disadvantages:
- Current error bars prevent any conclusions

Advantages:
- STAR year 7 data allow 4x statistics
- New method (Brooke Haag, QM08 poster) may allow even higher stats/higher p\textsubscript{T}
- Systematic errors due to v\textsubscript{2} at least move together
Summary

- Studies showing shape changes on away-side
  - Signal/Background > 1/20
  - Systematic errors due to $v_2$ large because background is large
    - $1 \text{ GeV/c} < p_T^{\text{associated}}$
    - Ridge yield significant on Near-side
    - $\Rightarrow$ ZYAM assumption could lead to significant errors
- We don't understand the near-side yet
  - $2.5 \text{ GeV/c}$ trigger (PHENIX) isn't very “jetty”
  - $3.0 \text{ GeV/c}$ (STAR) is only slightly better
  - $1 \text{ GeV/c} < p_T^{\text{associated}}$ - on near-side, Ridge dominates. Does this affect the away-side?
- How do we know that the production mechanisms for the Ridge and the shape changes on the away-side are distinct?
Outlook

- Higher $p_T$ on 3-particle correlations?
  - Really need higher $p_T^{\text{associated}}$, $p_T^{\text{trigger}}$ to understand results
  - More data not yet analyzed
  - DAQ upgrades which would allow more data in a run
  - Advances in triggering

- Need to understand the near-side
  - More data helps in particle ratios
  - More particles?

- Jet reconstruction in heavy ion collisions?
  - Some progress
  - Would allow reconstruction of near-side
Did I really make it this far?!?
$p_T$-distribution of associated particles

- Ridge spectra similar to the bulk
  - Cu+Cu measurements probably not possible
- Jet spectra are slightly harder
  - Cu+Cu $T$ within error of Au+Au

<table>
<thead>
<tr>
<th>Trigger particle</th>
<th>$T(\text{ridge})$ MeV</th>
<th>$T(\text{jet})$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>h/$^+$</td>
<td>438 ± 4 (stat.)</td>
<td>478 ± 8</td>
</tr>
<tr>
<td>$K^0_s$</td>
<td>406 ± 20 (stat.)</td>
<td>530 ± 61</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>416 ± 11 (stat.)</td>
<td>445 ± 49</td>
</tr>
</tbody>
</table>

Nattrass SQM 2007

445 ± 20 MeV

Fit to $A \exp(-p_T/T)$
Two Analysis Techniques

Measure 1-, 2-, and 3-Particle Densities

\[
\begin{align*}
\rho_1(j_i) & = \frac{d^2 N}{d j_i} \\
\rho_2(Dj_{ij}) & = \frac{d^2 N}{d Dj_{ij}} \\
\rho_3(Dj_{ij},Dj_{ik}) & = \frac{d^3 N}{d Dj_{ij} d Dj_{ik}}
\end{align*}
\]

3-particle densities = superpositions of truly correlated 3-particles, and combinatorial components.

We use **two approaches** to extract the truly correlated 3-particles component:

- **Cumulant technique:**

  \[
  C_3(\Delta \phi_{12}, \Delta \phi_{13}) = \rho_3(\Delta \phi_{12}, \Delta \phi_{13}) - \rho_2(\Delta \phi_{12})\rho_1(3) - \rho_2(\Delta \phi_{13})\rho_1(2) \\
  - \rho_2(\Delta \phi_{13} - \Delta \phi_{12})\rho_1(1) + 2\rho_1(1)\rho_1(2)\rho_1(3)
  \]

- **Jet+Flow Subtraction Model:**

  \[
  J_3(\Delta \phi_{12}, \Delta \phi_{13}) = \nu_3(\Delta \phi_{12}, \Delta \phi_{13}) - \nu_2(\Delta \phi_{12})B_2(\Delta \phi_{13}) \\
  - \nu_2(\Delta \phi_{13})B_2(\Delta \phi_{12}) - B_3(\Delta \phi_{12}, \Delta \phi_{13})
  \]

**PROs**

Simple Definition  
Model Independent.

**CONs**

Not positive definite  
Interpretation perhaps difficult.

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See poster 36 by C. Pruneau & nucl-ex/0608002  
See poster 44 by J. Ulery & nucl-ex/0609017/0609016
Measurement of 3-Particle Cumulant

- Clear evidence for finite 3-Part Correlations
- Observation of flow like and jet like structures.
- Evidence for $v_2 v_2 v_4$ contributions
3-Cumulant vs. centrality

Au + Au 80-50%  30-10%  10-0%

• $k_T$? Interplay of jet & flow?
Cone Angle (radians)

- Au+Au 0-12% (shifted)
- Au+Au 30-50%, 10-30% and 0-10%

1.47±0.02
3-particle correlations: STAR

- Trigger particle $3<p_T<4$ GeV/c with pairs of associated particle $1<p_T<2$ GeV/c..

- Complicated background...
  - Raw signal contains $(\text{Jet} + \text{Bkgd}) \otimes (\text{Jet} + \text{Bkgd})$.
  - To obtain $\text{Jet} \otimes \text{Jet}$ we must subtract $\text{Bkgd} \otimes \text{Bkgd}$ and $\text{Jet} \otimes \text{Bkgd}$ (and $\text{Bkgd} \otimes \text{Jet}$.)
Jet and Jet+Ridge yields & widths

Correlate Jet ($\Delta \eta(J)$) and Jet+Ridge ($\Delta \phi(J+R)$) widths & yields via centrality

- Jet+Ridge yield increasing with centrality
- Jet+Ridge shape asymmetric in $\Delta \eta$ and $\Delta \phi$
Jet yields & widths: $\Delta \eta$ vs. $\Delta \phi$

Correlate Jet ($\Delta \eta(J)$) and Jet ($\Delta \phi(J)$) widths and yields via centrality

- Jet yield ~ symmetric in $\Delta \eta \times \Delta \phi$
- Jet shape ~ symmetric in $\Delta \eta \times \Delta \phi$ for $p_{t,\text{trig}} > 4$ GeV
  (asymmetric in $\Delta \eta$ for $p_{t,\text{trig}} < 4$ GeV)

STAR preliminary
Jet and Jet+Ridge yields & widths

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