Studies of Jets through Correlations in Heavy Ion Collisions at RHIC

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Introduction

● Why study jets in heavy ion collisions?
● The near-side
● The away-side
● Conclusions
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
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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
RHIC

- Luminosity
  \( \sim 2 \cdot 10^6 \text{ cm}^{-2}\text{s}^{-1} \)
- Can collide multiple species (Au+Au, Cu+Cu, d+Au, p+p...)
- Interaction diamond <20 cm long
- 56 bunches
- \( 10^9 \) ions/bunch
- nominal 10 hour store time
- 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

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

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

Expected because higher $p_T^{\text{trigger}}$ should be “jettier”

Ridge yield decreases

Ridge dominant in central Au+Au

pT trigger dependence of Jet and Ridge

Jet

Ridge

J. Bielcik QM06
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 $N_{\text{part}}$  

Identified triggers:

- **Jet yield**
  - Nearly flat with $N_{\text{part}}$ 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 $N_{\text{part}}$ in Cu+Cu and Au+Au
  - No trigger dependence within errors

### STAR preliminary

$\sqrt{s_{NN}}=200$ GeV, $|\Delta\eta|<0.7$

data points at same $N_{\text{part}}$ offset for visibility

Jet yields: 10% error added to $V^0$ and h triggers to account for track merging, 15% to $\Xi$ triggers

Christine Nattrass  
Banska Bystrica, Jan. 4, 2007
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
  - No \( v_2 \) or background error due to method
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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

\[ \sqrt{s_{NN}} = 200 \text{ GeV}, |\Delta\eta| < 1.7 \]

STAR preliminary

Cu  Au

Jet yield:
- Nearly flat with \( N_{\text{part}} \) within errors across d+Au, Cu+Cu, Au+Au
- No \( v_2 \) or background error due to method
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Ridge yield:
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Jet yields: 10% error added to \( V^0 \) and \( h \) triggers to account for track merging, 15% to \( \Xi \) triggers

C. Nattrass SQM07
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_{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
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

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 $p_T^{\text{associated}}$
Away-side: Motivation

Or STAR results...

- Shape distortion increases with centrality
- Decreases with increasing $p_T^{\text{trigger}}$
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Centrality

60-80%
40-60%
20-40%
0-12%
**Away-side: Motivation**

Or STAR results...

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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 ➔ can't distinguish
3-particle correlations

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

STAR
\[ \Delta \phi \Delta \phi \text{ space (} \Delta \phi = \phi - \phi_{\text{Trigger}}) \]

Ulery (STAR) QM’05

Ajitanand (PHENIX) HP06, IWCF’06

• PHENIX
• polar coordinates
Conclusions

- Jets have proven to be a powerful probe at RHIC
  - The near-side is modified
    - The Jet
      - Looks like vacuum fragmentation
    - The Ridge
      - Looks very similar to the bulk
  - Away-side is modified

- Many proposed models, more work to do
Da steh' ich nun, ich armer Tor,
Und bin so klug als wie zuvor!

Faust I
Goethe
Away-side: Motivation

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

Whether we look at PHENIX results...
3-particle correlations: PHENIX

Need to work on this slide, colors, etc.

Christine Nattrass
Banska Bystrica, Jan. 4, 2007
3-particle correlations: PHENIX

Need to work on this slide, colors, etc.

**Trigger**

- $2.5 < p_T^{\text{Trig}} < 4$ GeV/c
- $1 < p_T^{\text{Assoc}} < 2.5$ GeV/c

**Same Side**

- $\Delta \phi^*$
- $\theta^*$

**Away Side**

- $\Delta \phi_{12}$

**Near-side**

Ajitanand (PHENIX) HP06

Christine Nattrass  Banska Bystrica, Jan. 4, 2007
3-particle correlations: PHENIX

Need to work on this slide, colors, etc.

Same Side

Away Side

\[ 2.5 < p_T^{\text{Trig}} < 4 \text{ GeV/c} \]

\[ 1 < p_T^{\text{Assoc}} < 2.5 \text{ GeV/c} \]

Au+Au 0-5 %

Ajitanand (PHENIX) HP06

Away-side
3-particle correlations: PHENIX

Deflected jet simulations

Mach Cone simulations

Same Side

Away Side

Normal jet simulations

SIM Normal Jet Correlation PHENIX Acceptance
2.5<p_{T}\text{Trig}<4\text{ GeV/c} 1<p_{T}\text{Assoc}<2.5\text{ GeV/c}

40-60 %

10-20 %

0-5 %

huh?

Hugo Pereira SQM 07

2.5<p_{T}\text{Trig}<4\text{ GeV/c} 1<p_{T}\text{Assoc}<2.5\text{ GeV/c}

Ajitanand (PHENIX) HP06

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3-particle correlations: PHENIX

Ajitanand (PHENIX) HP06, IWCF’06

Δφ* Projections

- Δφ* Projections
- Projections
- v₂ subtracted

● Dependent on background subtraction
● Details of background subtraction not shown
● Central data not shown

Christine Nattrass
Banska Bystrica, Jan. 4, 2007
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 < \( p_T^{\text{associated}} \) < 2 GeV/c, 3 < \( p_T^{\text{trigger}} \) < 4 GeV/c

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

- On-diagonal and off-diagonal projections.
- Yellow bands are systematic errors.
- Significant off-diagonal peaks.
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 $K^0_S$ 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 $p_T$
- Systematic errors due to $v_2$ 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
    - 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
  - Detector 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
Backup slides
**Reminder: Background Subtraction**


Before background subtraction

After background subtraction

1 $< p_T^{assoc} < 2.5 < p_T^{trigg} < 4$ GeV/c

Au+Au 200 GeV 0-5%

No dip before background subtraction

Signal sits on top of large background

Assumption that there is no yield at minimum

Dip appears after background subtraction
A caveat...

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

![Graph showing $N_{counts}/\Delta\phi N_{\text{trigger}}$ for $\Lambda-h^\pm$ and $\Lambda-h^\pm \nu_2$.](image.png)

0-10% central AuAu

- $2.5 < p_T\text{-Trigger} < 4.5 \text{ GeV/c}$
- $1.5 < p_T\text{-Assoc} < p_T\text{-Trig}$

Open points: reflected function

STAR Preliminary

J. Bielcikova QM06
Determination of yields and errors

- Background:
  \[ B(1 + 2v_{\text{trig}}^2 v_{\text{assoc}}^2 \cos(2\Delta\Phi)) \]
  \( v_2 \) – 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 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!
**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
  - $-0.75 < \Delta \eta < 0.75$ *Jet + Ridge*
  - $0.75 < |\Delta \eta| < 1.75$ *Ridge*

  \[ \text{Jet} = (\text{Jet} + \text{Ridge}) - \text{Ridge}^*.75/1.75 \]

- *Ridge* = yield from
  - $-1.75 < \Delta \eta < 1.75$ – *Jet* yield

- Flow contributions to jet cancel
  - $v_2$ flat with $\eta$ for $|\eta| < 1$

$p_T$-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>$Λ$</td>
<td>416 ± 11 (stat.)</td>
<td>445 ± 49</td>
</tr>
</tbody>
</table>

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

Nattrass SQM 2007
Two Analysis Techniques

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

\[ \rho_1(j_i) \propto \frac{d^2 N}{dj_i} \quad \rho_2(D_{ij}) \propto \frac{d^2 N}{dD_{ij}} \quad \rho_3(D_{ij}, D_{ik}) \propto \frac{d^3 N}{dD_{ij} dD_{ik}} \]

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:**

  \[ \tilde{f}_3(\Delta \phi_{12}, \Delta \phi_{13}) = \psi_3(\Delta \phi_{12}, \Delta \phi_{13}) - \tilde{\psi}_2(\Delta \phi_{12})B_2(\Delta \phi_{13}) \]

  \[ - \tilde{\psi}_2(\Delta \phi_{13})B_2(\Delta \phi_{12}) - B_3(\Delta \phi_{12}, \Delta \phi_{13}) \]

**PROs**

Simple Definition

Model Independent.

**CONS**

Not positive definite

Interpretation perhaps difficult.

**PROs**

Intuitive in concept

Simple interpretation in principle.

**CONS**

Model Dependent

\( v_2 \) and normalization factors systematics.

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 $v_2v_2v_4$ contributions

$\rho_2(23) r_1(1)$

$C_3(\Delta \phi_{12}, \Delta \phi_{13})$
3-Cumulant vs. centrality

Au + Au 80-50%

30-10%

10-0%

- \kappa_T? Interplay of jet & flow?
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 ($\Delta \eta$) and Jet+Ridge ($\Delta \phi$) 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 ($\Delta \phi$):
- 3 < $p_t$(trig) < 4
- 4 < $p_t$(trig) < 5
- 5 < $p_t$(trig) < 6
- 6 < $p_t$(trig) < 12

Jet width ($\Delta \eta$):
- 3 < $p_t$(trig) < 4
- 4 < $p_t$(trig) < 5
- 5 < $p_t$(trig) < 6
- 6 < $p_t$(trig) < 12

• Jet yield ~ symmetric in $\Delta \eta \times \Delta \phi$
• Jet shape ~ symmetric in $\Delta \eta \times \Delta \phi$ for $p_t$,assoc. > 2 GeV
  (asymmetric in $\Delta \eta$ for $p_t$,assoc. < 4 GeV)

05/25/08
Purdue University December 10th

Christine Nattrass
Banska Bystrica, Jan. 4, 2007
A caveat...

- Large background subtraction
3-particle correlations: STAR background

- Add page(s) w/ equations
Jet and Jet+Ridge yields & widths

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

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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 $\sim$ symmetric in $\Delta \eta \times \Delta \phi$
- Jet shape $\sim$ 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)

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Away-side: Motivation

- See shape change in 2-D correlations
- apparent peak at dphi \neq \pi
- already see strong dependence on the background subtraction
- Qualitatively STAR and PHENIX see the same thing
- shape change as you go peripheral \rightarrow central
- quantitatively STAR and PHENIX disagree dramatically on size of systematic errors
3-particle correlations

- Two different approaches to measurement with different ways of plotting data
- Similar qualitative results – weak support for conical emission
- Statistical errors - can be reduced
- Systematic errors – can they be reduced?