Precision measurements of jet-like correlations
And what they teach us about flow

Christine Nattrass
Contributions from Natasha Sharma, Joel Mazer, Meg Stuart, Aram Bejnood
Jets and flow

- Both lead to azimuthal correlations
- Jets $\rightarrow$ background for flow
- Flow $\rightarrow$ background for jets

Overview

- New method for separating jets from flow
- Apply it to data
  - Di-hadron correlations
  - Jet-hadron correlations
- And what we learn about flow from jet-like correlations
Methods
Two component model

- Assume contributions can be factorized
- Alternately, define signal as anything which isn't consistent with separable flow and jet components
- Assumptions even embedded in studies of full jets
Zero Yield At Minimum

- Flow component given by
  \[ B \left( 1 + \sum_{n=2}^{\infty} v_n^t v_n^a \cos(n \Delta \phi) \right) \]
- Fix background level at minimum
- Use independent measurements of \( v_n \)
Issues with ZYAM

- Tends to underestimate background level
  - Can use fixed point (e.g. \( \Delta \phi = 1 \)) instead
- \( v_n \) for background may not be the same as independent measurements
  - Cumulant methods suppress fluctuations \( v_n < \tilde{v}_n \)
  - Reaction plane measurements may include effects from jets \( v_n > \tilde{v}_n \)
  - Events with jets may be different \( v_n \neq \tilde{v}_n \)
  - High and low \( p_T \) reaction planes may be different \( v_n \neq \tilde{v}_n \)
- If jet peak is broadened, may overestimate background (underestimate signal)
Background Subtraction Methods

- **Δη Method**: Project near-side signal onto Δη and subtract constant background. **Near-side only**
- **Δη Gap Method**: Use signal at large Δη to determine background, assuming constant background in Δη. **Near-side only**
- **Zero-Yield at Minimum (ZYAM)**: Assumes $v_n$ from other studies, assumes region around $\Delta \phi \approx 1$ is background dominated
Separating the signal and the background

Toy model:
- Signal: PYTHIA
- Background: thrown to $v_n = 10$ to match data
- Details in backup and paper
Signal vs background

Signal+background

Signal only

Background dominated region

\( h-h \)
\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)
30-40\% PbPb
8 < \( p_T^{\text{trigger}} < 10 \text{ GeV/c} \)
1 < \( p_T^{\text{assoc}} < 2 \text{ GeV/c} \)
Near-Side Fit (NSF) method

No reaction plane dependence

- Project signal+background over $1.0 < |\Delta \eta| < 1.4$
- Fit background in $|\Delta \phi| < \pi/2$ with $v_n$ up to $n=4$
Near-Side Fit (NSF) method

No reaction plane dependence

- Reconstruc\textit{ts} signal with less bias and smaller errors than ZYA1 method
- Extract $v_n$ consistent with input

<table>
<thead>
<tr>
<th>Sample</th>
<th>Yield ($Y \times 10^{-3}$)</th>
<th>Near-side</th>
<th>Away-side</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
<td>17.1 ± 0.1 ± 0.2</td>
<td>19.9 ± 0.1 ± 0.2</td>
<td></td>
</tr>
<tr>
<td>Mod. ZYA1</td>
<td>18.9 ± 4.2 ± 1.2</td>
<td>21.9 ± 4.2 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>Std. ZYA1</td>
<td>15.7 ± 1.6 ± 1.2</td>
<td>18.7 ± 1.6 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>NSF</td>
<td>17.14 ± 1.1</td>
<td>20.14 ± 1.11</td>
<td></td>
</tr>
</tbody>
</table>

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

30-40\% PbPb

8<p_T^{\text{trigger}}<10 \text{ GeV/c}

1<p_T^{\text{assoc}}<2 \text{ GeV/c}

Standard ZYA1 = Zero Yield at $\Delta \Phi=1$

Modified ZYA1 = Zero Yield at $\Delta \Phi=1$ for 1.0<|$\Delta \eta$|<1.4
Near-Side Fit (NSF) method

No reaction plane dependence

Signal+background

- Project signal+background over $1.0 < |\Delta \eta| < 1.4$
- Fit background in $|\Delta \phi| < 1$
- Not reliable over narrower $\Delta \phi$ region

h-h
$\sqrt{s_{NN}} = 2.76$ TeV
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Adding reaction plane dependence
Background in correlations

- All reaction plane angles

\[ B(1 + \sum_{n=2}^{\infty} v_n^t v_n^a \cos(n \Delta \phi)) \]

- When trigger is restricted relative to reaction plane
  
  - Background level modified

\[ B = 1 + \sum_{k=2}^{\infty} 2 v_k^a v_k^{R,t} \cos(k \phi_S) \frac{\sin(kc)}{kc} R_n \]

  - Effective \( v_n \) modified

\[ v_n^R,t = \frac{v_n + \cos(n 8_s) \frac{\sin(nc)}{nc} R_n + \sum_{k=2,4,6...}^{\infty} (v_{k+n} + v_{k-n}) \cos(k \phi_S) \frac{\sin(kc)}{kc} R_n}{1 + \sum_{k=2,4,6...}^{\infty} 2 v_k \cos(k \phi_S) \frac{\sin(kc)}{kc} R_n}, \text{ n=even} \]

\( \phi_S \) is the angular threshold

\[ R_n = \langle \cos(n (\psi_{true} - \psi_{reco})) \rangle \]

Reaction Plane Fit (RPF) method
30-40% central

- Project signal+background over $1.0 < |\Delta \eta| < 1.4$
- Fit background in $|\Delta \phi| < 1$ including reaction plane dependence
- $v_n$ and B extracted with $v_n$ up to $n=4$

Christine Nattrass (UTK), Winter Workshop on Nuclear Dynamics, January 2017
Reaction Plane Fit (RPF) method

30-40% central

\[
\frac{1}{N_e} \frac{d^2 N}{d \phi \, d \Delta t} \]
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- **Reaction Plane Fit (RPF):** assumes small $Δφ$/large $Δη$ region background dominated, fits $v_n$ and B using reaction plane dependence

- **Near-Side Subtracted NSF/RPF (NSS NSF/RPF):** fits $v_n$ and B at small small $Δφ$ using reaction plane dependence after subtracting the near-side with a fit
STAR data
STAR measurements of dihadron correlations relative to reaction plane

- Correlations on arxiv (nucl-ex/1010.0690 v2)
  - Published article (Phys. Rev. C 89 (2014) 41901) does not include raw correlations

- ZYAM background subtraction
  - Reports ridge at $\Delta \eta > 0.7$
  - RPF method assumes no signal at $\Delta \eta > 0.7$
Dihadron correlations

\[ 0 < \phi - \psi < \pi/12 \]
\[ \pi/12 < \phi - \psi < 2\pi/12 \]
\[ 2\pi/12 < \phi - \psi < 3\pi/12 \]
\[ 3\pi/12 < \phi - \psi < 4\pi/12 \]
\[ 4\pi/12 < \phi - \psi < 5\pi/12 \]
\[ 5\pi/12 < \phi - \psi < 6\pi/12 \]

\[ p+p \text{ min. bias} \]
\[ \text{Au+Au Central} \]

\[ 4.0 < p_T^{\text{trig}} < 6.0 \text{ GeV/c} \]

\[ 2.0 < p_T < 3.0 \text{ GeV/c} \]

\[ 3.0 < p_T < 4.0 \text{ GeV/c} \]

\[ \Delta \phi \text{ (radians)} \]


ALICE data

Joel Mazer: Hot Quarks 2016, Quark Matter 2017
1.0-1.5 GeV/c $p_T^{assoc}$

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit

Correlation function

- Uncertainties dominated by statistics
- Background uncertainty is non-trivially correlated point-to-point
1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit

Correlation function

\[ \rho^{\text{ch}, c, E_{\text{clus}}^{\text{lead,clus}} > 3.0 \text{ GeV}, 1.5 < p_{T}^{\text{assoc}} < 2.0} \]

Background uncertainty is non-trivially correlated point-to-point

\( v_3 \) and \( v_4 \) components important

\( \chi^2/\text{NDF} = 0.879 \)
Correlation function

Away side clearly there and suppressed
1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit

Correlation function

4.0-5.0 GeV/c $p_T^{assoc}$

- In-plane
  - \( p_T^{assoc}, E_T^{clus} > 3.0 \text{ GeV} \)
  - \( E_T^{lead \, plus} > 6 \text{ GeV} \)
  - \( 4.0 < p_T^{assoc} < 5.0 \)

- Mid-plane
  - Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV}, \text{30-50}\% \)
  - Anti-k, full jets, R=0.2
  - \( p_T^{ch+re} = 20-40 \text{ GeV/c} \)

- Out-of-plane
  - Background: \( 0.8 < |\eta| < 1.2 \)
  - Signal+Background: \( |\eta| < 0.6 \)

ALICE Preliminary

\( \chi^2/NDF = 1.010 \)

Correlation function

- In-plane
  - \( 4.0 < p_T^{assoc} < 5.0 \)
  - \( |\Delta\eta| < 0.6 \)
  - ALICE Preliminary

- Mid-plane
  - Pb-Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV}, \text{30-50}\% \)
  - Anti-k, full jets, R=0.2
  - \( p_T^{ch+re} = 20-40 \text{ GeV/c} \)

- Out-of-plane
  - \( p_T^{ch}, E_T^{clus} > 3.0 \text{ GeV} \)
  - \( E_T^{lead \, plus} > 6.0 \text{ GeV} \)

All angles

Scale Uncertainty 6.0%
What about flow?
• Different $v_n$ from RPF method for $h-h$ correlations
• Same $v_n$ as inclusive studies from RPF for jet-$h$ correlations
One of the following must be true:

- $v_n^{\text{jet}} \neq v_n^{\text{bkgd}}$
  - Dihadron correlations:
    - Background: J-B, B-J, B-B
    - Signal: J-J
  - Jet-hadron correlations: fake jets negligible
    - Background: J-B
    - Signal: J-J
- Hard and soft rxn planes decorrelated
  - Soft rxn plane reconstructed
    \[
    B(1 + \sum_{n=2}^{\infty} v_n^{t} v_n^{a} \cos(n \Delta \phi)) = B(1 + \sum_{n=2}^{\infty} v_{n,\text{corr}}^{t} (1 + \frac{v_{n,\text{uncorr}}^{t}}{v_{n}^{t}}) v_n^{a} \cos(n \Delta \phi))
    \]
- Reaction plane measurements may include effects from jets
- Events with jets have different flow
Conclusions

- RPF method is robust
  - Allows studies of away side
  - Move beyond ZYAM.
- Precision correlation studies possible
  - No more Mach cone!
- Jets exhibit little/no reaction plane dependence
- Something interesting is going on with flow
Toy model
Model for signal

- Use PYTHIA Perugia 2011
- $\pi^\pm$, $K^\pm$, $\bar{p}$, $p$ for unidentified hadrons
- Quarks and gluons as proxy for reconstructed jets

$h-h$

$\sqrt{s} = 2.76$ TeV

pp collisions

$8 < p_T^{\text{trigger}} < 10$ GeV/c

$1 < p_T^{\text{assoc}} < 2$ GeV/c
Model for background

- True reaction plane angle is always at $\phi=0$ in detector coordinates
- Throw random reconstructed reaction plane angle
  - Assume Gaussian reaction plane resolution
  - Selected to approximate data
- Use measured particle yields to calculate how many associated particles would be measured
- Use measured $v_n$ to determine their anisotropy relative to the reaction plane
- Throw associated particles matching distribution observed in data using $v_n$ up to $n=10$
Acceptance correction

- Fixed acceptance cuts leads to a trivial structure due to acceptance

- This is fixed with a “mixed event” correction
  - Throw random trigger, associated particle within acceptance
  - Calculate $\Delta \phi$, $\Delta \eta$
  - Use this distribution to correct for acceptance
Going to lower momenta
Low momenta

- ZYAM assumptions break down at low $p_T$
- If method doesn't work on PYTHIA, it can't be trusted on data!
- But low $p_T$ is interesting!
Going to lower momenta, medium modifications

- Peak gets broader
- Fit near-side peak and subtract it
- Increase $\Delta \eta$ range available for background subtraction

$h-h, \sqrt{s}_{\text{NN}} = 2.76 \text{ TeV}, 0\text{-}10\% \text{ PbPb}$
$8 < p_T^{\text{trigger}} < 10 \text{ GeV/c}$
$1 < p_T^{\text{assoc}} < 2 \text{ GeV/c}$ for background, $0.5 < p_T^{\text{assoc}} < 1.0 \text{ GeV/c}$ for signal

Structure from imperfect fit
Near-Side Subtracted RPF method
30-40% central

- Project signal+background over \(0.0 < |\Delta \eta| < 1.4\)
- Fit background in \(|\Delta \phi| < 1\) including reaction plane dependence
- \(v_n\) and B extracted with \(v_n\) up to \(n=4\)
Reaction Plane Fit (RPF) method
30-40% central

- Works beautifully!
Stages of a heavy ion collision
Jets – azimuthal correlations

\[ p+p \rightarrow \text{dijet} \]

Select high momentum particles → biased towards jets

\[ \Delta \phi (\text{radians}) \]

\[ 1/N_{\text{Trigger}} \frac{dN}{d(\Delta \phi)} \]

\[ p+p \text{ min. bias} \]

\[ 4<p_T(\text{trig})<6 \text{ GeV/c} \]

\[ p_T(\text{assoc})>2 \text{ GeV/c} \]
Azimuthal correlations

\[ \frac{1}{N_{\text{Trigger}}} \frac{dN}{d(\Delta \phi)} \]

- **p+p min. bias**
- **Au+Au Central**

*STAR*

Competing effects

Quenching
Fewer jets, lower yield out of plane

Bremsstrahlung
Softer, higher yield out of plane

Fluctuations
Individual jets' energy loss may vary
Dihadron correlations


Near-side jet yields vs EP

Jets 20-40 GeV/c, 30-50% centrality

Within uncertainties of current statistics, no event plane ordering

Black symbols: Different effects in different $p_T$ associated bins

Competing effects
1) Quenching
2) Bremsstrahlung
3) etc

$\sqrt{s_{NN}} = 2.76$ TeV, 30-50%
Anti-$k_T$ full jets, R=0.2
$p_{T,\text{unc.},\text{jet}}^{\text{ch+ne}} = 20-40$ GeV/c
$p_T^{\text{ch}, E_{T,\text{clus}}^\text{lead}} > 3.0$ GeV
$E_T^{\text{clus}} > 6.0$ GeV

Scale uncertainty 6%

Point displaced for visibility

$|\Delta \eta| < 0.6$
NS yield range: $-1.047 < \Delta \phi < 1.047$

ALICE Preliminary
Away-side jet yields vs EP

Jets 20-40 GeV/c, 30-50% centrality

Pb-Pb $\sqrt{s_{NN}} = 2.76$ TeV, 30-50%
Anti-$k_T$ full jets, $R=0.2$
$p_{T\,unc,\,jet}^{ch+ne} =$ 20-40 GeV/c
$p_{T\,c}, E_T^{clus} > 3.0$ GeV
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Within uncertainties of current statistics, no event plane ordering
- Different effects in different $p_T$ associated bins

Competing effects
1) Quenching
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3) etc

ALICE Preliminary
$|\Delta \eta| < 0.6$
AS yield range: $2.094 < \Delta \phi < 4.189$
points displaced for visibility

In-plane
Mid-plane
Out-of-plane
Background unc.
Scale uncertainty 6%
PYTHIA at 200 GeV

8<p_T<10 GeV/c
PYTHIA at 200 GeV

Nearside $\Delta \phi$

Awayside $\Delta \phi$

3$p_T^t$<4 GeV/c

4$p_T^t$<6 GeV/c

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Near-Side Subtracted NSF method

- Project signal+background over \(0.0 < |\Delta \eta| < 1.4\)
- Fit background in \(|\Delta \phi| < 1\) including reaction plane dependence
- Bias from residual contamination by near-side
Correlations - STAR

- Green: d+Au, Red: Au+Au
- Large error bars
- “Mach Cone” evident, even decrease in amplitude for higher $p_T$
Background subtracted correlations $4<p_T^t<6$ GeV/c

Yellow bands: uncertainty in rescaling of background
Statistical error bars include correlated statistical error on background

No "Mach Cone"
RPF Method

- 6 bins relative to reaction plane
- Background level
  - Normalized per trigger → B same in all bins if $v_2^t$ is the only effect → reduces info for RPF
  - “The background levels can be different for the different $\phi_s$ slices because of the net effect of the variations in jet-quenching with $\phi_s$ and the centrality cuts in total charged particle multiplicity in the TPC within $|\eta| < 0.5$.” (Pg. 10, arxiv version) → Not consistent with ZYAM assumptions!
- Used reaction plane resolution values from paper and their uncertainties
  - Used TPC for reaction plane and analysis – potential autocorrelations
- Data available for $\Delta \eta < 0.7$ (signal+background) and $0.7 < \Delta \eta < 2$ (background dominated)
  - Acceptance correction in not applied → background must be scaled → uncertainty
  - Jet-like correlation not eliminated in $0.7 < \Delta \eta < 2$ for all $p_T^t$, $p_T^a$ given in paper → focus on high $p_T$
\( v_2 \) STAR vs Fit

<table>
<thead>
<tr>
<th>( p_T ) Bin</th>
<th>( v_2 ) STAR (Table I)</th>
<th>( v_2 ) Fit (stat. errors only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5&lt;( p_T )&lt;2.0 GeV/c</td>
<td>0.164 ± 0.011</td>
<td>0.194 ± 0.008</td>
</tr>
<tr>
<td>2.0&lt;( p_T )&lt;3.0 GeV/c</td>
<td>0.189 ± 0.012</td>
<td>0.237 ± 0.010</td>
</tr>
<tr>
<td>3.0&lt;( p_T )&lt;4.0 GeV/c</td>
<td>0.194 ± 0.013</td>
<td>0.293 ± 0.058</td>
</tr>
<tr>
<td>4.0&lt;( p_T )&lt;6.0 GeV/c</td>
<td>0.163 ± 0.020</td>
<td>0.073 ± 0.025</td>
</tr>
</tbody>
</table>

- Centrality bin is 20-60% - proper weighting of average?
- Bias in event selection with high \( p_T \) trigger?
- Bias in reconstructed reaction plane in the presence of a jet?
- Residual jet-like signal in background dominated region?
- Less information in fit due to normalization by \( N_{\text{trigger}} \)?
Jets – azimuthal correlations

\[ p+p \rightarrow \text{dijet} \]

Select high momentum particles → biased towards jets

\[ 1/N_{\text{Trigger}} \frac{dN}{d(\Delta \phi)} \]

\[ \Delta \phi \text{ (radians)} \]

**Graph:**
- **Legend:**
  - \( p+p \) min. bias
  - \( 4<p_{T}(\text{trig})<6 \text{ GeV/c} \)
  - \( p_{T}(\text{assoc})>2 \text{ GeV/c} \)

**Source:**
- Phys Rev Lett 90, 082302

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Azimuthal correlations

\[ \frac{1}{N_{\text{Trigger}}} \frac{dN}{d(\Delta \phi)} \]

- p+p min. bias
- Au+Au Central


\[ \Delta \phi \ (\text{radians}) \]
Dihadron correlations

Sharma, Mazer, Stuart, Nattrass: *(Phys. Rev. C 93, 044915 2016)*
Dihadron correlations

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Joel Mazer
Hot Quarks 2016
Little/no path length dependence?

• Path length dependence naively predicted by every model
  – No path length dependence seen in rxn plane dependent $A_j$ either
• Insufficient sensitivity?
• Statistical variation in energy loss is more important than path length dependence
Bias

- Modified jets probably look more like the medium
- Quark jets are narrower, have fewer tracks, fragment harder [Z Phys C 68, 179-201 (1995), Z Phys C 70, 179-196 (1996)]
- Gluon jets reconstructed with $k_T$ algorithm have more particles than jets reconstructed with anti-$k_T$ algorithm [Phys. Rev. D 45, 1448 (1992)]
- Gluon jets fragment into more baryons [EPJC 8, 241-254, 1998]