High $p_T$ Azimuthal Correlations: What has been measured and what can they tell us?

David Hardtke (LBNL)
Outline

• Do we see jets in Au+Au collisions at RHIC?
  – Intrajet correlations (small $\Delta \phi, \Delta \eta$) -- STAR and PHENIX
    • Correlation widths
    • Relative Charge

• What happens to dijets?
  – Back-to-back dihadrons (large $\Delta \phi$, all $\Delta \eta$) -- STAR

• Distinguishing initial- and final-state nuclear effects
What is a jet?

Hard-scattering of parton followed by fragmentation into several hadrons:

QCD Factorization:

\[
\frac{d\sigma}{dp}(\pi) = \int dx_a \int dx_b f(x_a) f(x_b) \frac{d\sigma}{dP}(a + b \rightarrow c) D_{c \rightarrow \pi}(P,p)
\]

structure function

fragmentation function

pQCD
Jets in heavy-ion collisions

- Partons lose energy due to induced gluon radiation: “Jet Quenching”
  - Energy loss is measure of gluon density ⇒ Indirect QGP signature

Nuclear Medium

ProBE energy loss via leading hadrons and di-hadron correlations
Jets in AuAu? The Challenge

Find this ……………………………………………….in here

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

Central Au+Au Event

December 2002
RHIC/INT

David Hardtke - LBNL
Two-particle azimuthal correlations

- Identify jets on a statistical basis
- What we measure:
  - Azimuthal Distributions (STAR charged-charged, PHENIX γ-charged)
    \[ D(\Delta \phi, \Delta \eta) = \frac{1}{N_{\text{TRIGGER}}} \frac{1}{\text{Efficiency}} N(\Delta \phi, \Delta \eta) \]
  - Correlation Functions (PHENIX charged-charged)
    \[ C(\Delta \phi) = \frac{N_{\text{real}}(\Delta \phi)}{N_{\text{mixed events}}(\Delta \phi)}, \quad \Delta \phi = |\phi_1 - \phi_2| \]
Sources of azimuthal correlations

- **Au+Au**
  - elliptic flow

- **p+p and Au+Au collisions:**
  - dijets
  - momentum conservation
  - jets
  - resonances

STAR Preliminary
Au+Au @ 200 GeV/c
0-5% most central
4<p_T(trig)<6 GeV/c
2<p_T(assoc.)<p_T(trig)
Relative Charge Dependence

Strong dynamical charge correlations in jet fragmentation →

Compare ++ and -- charged azimuthal correlations to +- azimuthal correlations

<table>
<thead>
<tr>
<th>System</th>
<th>(+-)/(++ &amp; --)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p</td>
<td>2.7±0.9</td>
</tr>
<tr>
<td>0-10% Au+Au</td>
<td>2.5±0.6</td>
</tr>
<tr>
<td>Jetset</td>
<td>2.6±0.7</td>
</tr>
</tbody>
</table>

Same particle production mechanism for pT>4 GeV/c in pp and central Au+Au
Feynman, Field, and Fox (1977):

“The existence of a towards correlations of about the expected size in both the like and unlike charge configuration is a particularly important test for the [parton scattering] model … It is worth emphasizing here that the quark scattering model predicts (++)/(+-) distinctly less the one … This distinctive quantum number structure seems to be borne out by the current experiments.”
Peripheral Fixed $p_\perp$ Correlation Function

Kinematically favoured near-angle peak

Kinematically disfavoured near-angle peak

December 2002

David Hardtke - LBNL

RHIC/INT

P. Constantin, DNP02
pQCD parton fragmentation in p-p collisions

\( j_\perp \) is the transverse momentum with respect to “jet” axis

\[ <| j_T |> = 400 \text{ MeV/c}, \]

independent of \( p_{\perp \text{Trig}} \)

for \( \sqrt{s} = 31, 45, 62 \text{ GeV} \)

CCOR Collaboration

Near-Angle Widths

P. Constantin, DNP02

The extracted width of the gaussian term (the dashed line - not a fit - corresponds to a constant $j_\perp = 400$ MeV):

Within the present errors, no evidence of broadening
Comparing Au+Au and p+p

- STAR ansatz: high $p_T$ triggered Au+Au event is superposition of high $p_T$ triggered p+p event and elliptic flow:
  \[ D(Au+Au) = D(p+p) + B*(1 + 2v_2^2 \cos(2\Delta\phi)) \]
  \[ I_{AA} = \frac{\int d(\Delta\phi)[D(Au+Au) - B*(1 + 2v_2^2 \cos(2\Delta\phi))]}{\int d(\Delta\phi)[D(p+p)\int]} \]
  - $v_2$ from reaction plane analysis
  - $B$: $I_{AA}(0.75<|\Delta\phi|<2.24) \equiv 1$

- Phenix analysis (M. Chiu, QM02)
  - pp data similar to pythia
  - Multiparameter fit
  \[ D(Au+Au) = Acc(\Delta\phi)\langle \epsilon \rangle(a_{bck} + a_{flow} \cos(2\Delta\phi) + a_{pythia} D(pythia)) \]
Phenix γ-charged analysis

Trigger on 2.5 GeV/c $\gamma \sim 2.8$ GeV/c $\pi^0$
Associate with 2-4 GeV/c charged hadrons
$|\Delta \eta|<0.7$

M. Chiu, et al., nucl-ex/0211008

20-40% centrality
Au+Au data vs. pp+flow

4<p_T(trig)<6 GeV/c
2<p_T(assoc)<p_T(trig)
|Δη|<1.4
$6 < p_T^{(\text{trigger})} < 8 \text{ GeV/c}$, $p_T^{(\text{associated})} > 2 \text{ GeV/c}$
$I_{AA}$ vs. Centrality and $p_T^{(trig)}$

Higher $p_T^{(trig)}$, smaller errors due to $v_2$ uncert.

Back-to-back dissappearance similar for all $p_T^{(trig)}$

Small-angle enhancement largest for smallest $p_T^{(trig)}$

$I_{AA}(\text{small } \Delta \phi) < 1$ for small $N_{part}$
What is $I_{\text{AA}}$?

- Small $\Delta \phi$:

$$I_{\text{AA}} = \frac{\int dE_T \frac{dN^{AA}}{dE_T} D_2^*(E_T, p_T^{\text{Trig}}, p_T^{\text{assoc}})}{\int dE_T \frac{dN^{AA}}{dE_T} D^* (E_T, p_T^{\text{Trig}}) + \text{soft}^{\text{AA}} (p_T^{\text{Trig}})}$$

$$+ \frac{\int dE_T \frac{dN^{pp}}{dE_T} D_2 (E_T, p_T^{\text{Trig}}, p_T^{\text{assoc}})}{\int dE_T \frac{dN^{pp}}{dE_T} D (E_T, p_T^{\text{Trig}}) + \text{soft}^{\text{pp}} (p_T^{\text{Trig}})}$$

Soft component at $p_T^{\text{(trig)}}$ reduces $I_{\text{AA}}$
Nuclear $k_T$?

Multiple nucleon interactions $\Rightarrow$ Nuclear $k_T$

Nuclear $k_T$ causes loss of acoplanarity for dijets.

Dijet events:

$$k_{T\phi} = p_T \sin \Delta \phi$$
Nuclear $k_T$

pp: $<k_T> \sim 1$ GeV/c  
pA: $<k_T> \sim 2$ GeV/c  
Vary intrinsic hadron $k_T$ to estimate possible effect:
Dijet Acoplanarity due to final-state?

- Fields and Corcoran [PRL 70 (1993)]
  - Little evidence for large nuclear $k_T$ in Drell-Yan
  - Dijet acoplanarity in pA due to final-state interaction
    - “Jet Broadening” ala BDMS:
      \[
      p_{\perp}^2 = \frac{\hat{q}(L)L}{(1-\alpha)}
      \]
      \[
      T^3 \tau^\alpha = \text{const.}
      \]
Hydro+Jet (Hirano and Nara)

- Near-side jets:
  Almost independent
- Away-side jets:
  Depend on magnitude of energy loss
Conclusions

• Conclusive evidence for jets in central Au+Au collisions from small-angle azimuthal correlations
  – STAR: Expected charge-ordering
  – PHENIX: Expected $j_T$ -- no evidence for jet width modifications
  – STAR: Enhancement of jet-like correlations with centrality

• Disappearance of back-to-back dihadrons seen by STAR
  – Need confirmation from Phenix
  – Similar for $p_T$(trig) = 3,4,6 GeV/c

• Missing dihadrons: Initial or Final State Effect?
  – No suppression of back-to-back dihadrons in pA at Fermilab, but acoplanarity increases with increasing A
  – Initial state nuclear kT -- small effect on magnitude of back-to-back correlations (Hijing and Hydro+Jet)
  – “Jet Broadening” needed at both Fermilab and RHIC Au+Au, but magnitude much larger at RHIC?
Remaining Questions and Outlook

• Why is proton/pion $\sim 1$ for central Au+Au while $I_{AA}(\text{small } \Delta \phi)>1$?
  – PHENIX: High $p_T$ azimuthal correlations for identified particles ($\pi^0$, proton, meson)
  – STAR: $\Lambda$, $K^0$ via topological decay? $\pi^0$ in next run

• At what $p_T(\text{trigger})$ do the dijets re-emerge? Direct measure of energy loss!
  – Need jet and $\pi^0$ triggers
Thanks!

- **PHENIX Students**
  - Mickey Chiu (Columbia)
  - Paul Constantin (Iowa State)

- **STAR Student**
  - Mike Miller (Yale)

- **Theorist**
  - Tetsufumi Hirano (Tokyo)
Hijing with energy loss

Hijing predicts little/no suppression of back-to-back correlations