Jet - flow($v_2$) correlation

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$v_2 - R_{AA}$
hydro, $N_{\text{quark}}$ scaling
energy loss, re-distribution
di-hadron correlation
mach-cone like shape
reaction plane dependence
left-right asymmetry
forward-backward asymmetry
Elliptic flow ($v_2$)

- hydro-model success
- quark degree of freedom
- high $p_T$ suppression from energy loss
- re-distribution of the lost energy

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Hadron large suppression
Direct $\gamma$ NO suppression
Jet suppression modification with 2-particle $\Delta \phi$ correlation

Jet suppression modification with 2-particle $\Delta \phi$ correlation

RHIC 200GeV

Au+Au 200 GeV 5-10%

PHENIX nucl-ex/0611019

Au+Au Central

p+p min. bias

d+Au FTPC-Au 0-20%

2.5 - 4 GeV/c $\times$ 2 - 3 GeV/c, All Charge

Centrality: 0 - 10%

Centrality: 30 - 40% $\times$ 0.33

Centrality: 60 - 92% $\times$ 0.046

SPS 17GeV

Au+Au 62.4 GeV 0-10%

S.Kniege, ISMD 2007

S.Kniege, ISMD 2007

Preliminary 17.2GeV, 0-5%
h-h correlation at “p+p 200GeV” vs “Au+Au 200GeV central 0-20%”

associate $p_T$ window

trigger $p_T$ window
RP dependent correlations

QM09, C. H. Chen

Au+Au $\sqrt{s_{NN}} = 200$ GeV - Cent 20-60%

$|p_T^A| \in [4.0,7.0] \text{ GeV/c}$

$|p_T^B| \in [4.0,5.0] \text{ GeV/c}$

$|\Delta \phi_A^\ast| \leq [0^\circ,15^\circ]$ (filled symbols)

$|\Delta \phi_A^\ast| \leq [75^\circ,90^\circ]$ (open symbols)

$\Delta = 0.66(3)$

near-side

away-side

in-plane

out-of-plane

2009/Sep/15, flow workshop, ECT* Trento

Shinichi Esumi, Univ. of Tsukuba
QM09, W. G. Holzmann

head: yield confirms simple picture of energy loss vs. path length; in- and out-of-plane show similar away-side width

shoulder: geometry effects harder to disentangle
If trigger angle is fixed around $\pm (\pi/4)$, the associate particles emitted left or right w.r.t. trigger direction would feel the different thickness of the almond. It is because the almond shaped medium is asymmetric w.r.t. jet axis.

Trigger angle selected with respect to the 2nd moment event plane $[-\pi/2, \pi/2]$ to probe the participant geometry.
Angle (4)/(5) (mid-central)

200GeV Au+Au -> h-h (run7)
($p_T^{\text{Trig}}=2\sim 4\text{GeV/c}$, $p_T^{\text{Asso}}=1\sim 2\text{GeV/c}$)
mid-central : 20-50%

(4) $\phi_s = [-1,0] \pi/8$

(5) $\phi_s = [0,1] \pi/8$

$\Delta \phi = \phi_{\text{Asso.}} - \phi_{\text{Trig.}}$ (rad)

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left/right asymmetry

in-plane associate regions
**Angle (3)/(6) (mid-central)**

- **200GeV Au+Au -> h-h (run7)**
  - \( p_T^{\text{Trig}} = 2-4\text{GeV/c} \), \( p_T^{\text{Asso}} = 1-2\text{GeV/c} \)
  - **Mid-central:** 20-50%

**Diagram:**
- Left/right asymmetry
- **\( \phi_s = [1,2]\pi/8 \)**
- **\( \phi_s = [-2,-1]\pi/8 \)**

**Graph:**
- **\( \Delta\phi = \phi_{\text{Asso.}} - \phi_{\text{Trig.}} \) (rad)**
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**Regions:**
- Left:
  - \( \phi_s = \phi_{\text{Trig.}} - \Phi_{\text{R.P.}} \) 
    - \([ -\pi/2, \pi/2 ] \)
- Right:
  - \( \phi_s = \phi_{\text{Trig.}} - \Phi_{\text{R.P.}} \) 
    - \([ -\pi/2, \pi/2 ] \)
200GeV Au+Au -> h-h (run7)
($p_T^{\text{Trig}}=2\sim4\text{GeV/c}$, $p_T^{\text{Asso}}=1\sim2\text{GeV/c}$)
mid-central : 20-50%

**Trigger angle selected curves are shifted up by constant offsets, dashed average lines are overlaid.**
200GeV Au+Au -> h-h (run7) ($p_T^{\text{Trig}}=2\sim4\text{GeV/c}$, $p_T^{\text{Asso}}=1\sim2\text{GeV/c}$)

Central: 0-20%
Mid-central: 20-50%
Peripheral: 50-93%

Delta phi = $\phi_{\text{Asso}} - \phi_{\text{Trig.}}$ (rad)

Black dashed line is same as the bottom average.

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200GeV Au+Au -> h-h (run7)  
($p_T^{\text{Trig}}=2-4\text{GeV/c}$, $p_T^{\text{Asso}}=1-2\text{GeV/c}$)  
mid-central : 20-50%  

Fitted data with 3 Gauss func.  

\begin{align*}  
\Delta \phi &= \phi_{\text{Asso}} - \phi_{\text{Trig}} \quad \text{(rad)} 
\end{align*}  

\begin{align*}  
\phi_s &= [-4,-3] \pi/8 
\end{align*}
4 different jet shape assumptions for MC input

jet shape #1
jet shape #2
jet shape #3
jet shape #4

near- and away-side dependence
only away-side dependence
only near-side dependence
no R.P. dependence
Comparison with data would tell us that there should be near- and away-side modification in experimental data.

There should also be a strong effect on $v_2$, much stronger effect on $v_4$. This gives natural explanation to the trigger particle bias on the associate $v_2$. 
$E_{\text{tot}} = 5 \text{ GeV}$
$p_T^{\text{trig}} = 3.5 \text{ GeV}$

broad away-side peak
due to non-central jets
double peaked structure

Satarov et al., PLB 627:64 (2005)
If the multiplicities reduces with the path length because of absorption...

Note: original jets are generated according to $N_{\text{coll}}$ profile
AMPT (v1.11, parton cascade with string melting v2.11) Au+Au at \( \sqrt{s_{NN}} = 200\text{GeV} \)

Similar trend as seen in experiment

\[
\phi_{\text{Asso.}} - \phi_{\text{Trig.}} \quad (\text{rad}) \quad \text{with trigger angle selected w.r.t. R.P.}
\]

\[
(p_{T\text{Asso.}} : 0.5\sim1.5\text{GeV/c} \quad p_{T\text{Trig.}} : 1.5\sim5.0\text{GeV/c})
\]

4\sim18\% \quad b = 3.5\sim7 \text{ (fm)}

44\sim4\% \quad b = 10.5\sim \text{ (fm)}

perfect R.P. resolution
no \( v_2 \) subtraction needed
Both near/away shapes show a strong $v_2$ (in-plane preference) as well as a strong left/right asymmetry (in-plane preference).

Ridge/Mach-cone like correlated pairs have been known to show similar properties as bulk in terms of inverse slope (apparent temperature) and particle ratios (Baryon/Meson).

STAR Preliminary

QM09 STAR

200GeV Au+Au 20-60\% ($p_{_{T\text{Trig}}} = 3\sim4\text{GeV/c}$, $p_{_{T\text{Assoc}}} = 1\sim1.5\text{GeV/c}$, $|\Delta\eta| > 0.7$, $\phi_{_{\text{Trig}}} - \phi_{_{\text{R.P.}}} < 0$)

QM08 STAR

200GeV Au+Au 20-60\% ($p_{_{T\text{Trig}}} = 3\sim4\text{GeV/c}$, $p_{_{T\text{Assoc}}} = 1\sim1.5\text{GeV/c}$, $|\Delta\eta| > 0.7$, $\phi_{_{\text{Trig}}} - \phi_{_{\text{R.P.}}} < 0$)

Ridge/Mach cone shape depends on R.P. angle.
Ridge/Mach cone (away side ridge) is a source of $v_2$

Jet does not depend on it.
Jet reduces $v_2$

Parallel aligning of several di-jets with R.P. because of almond geometry + $E_{\text{loss}}$. 

$\Delta\phi = \phi_{_{\text{Assoc}}} - \phi_{_{\text{Trig}}} \text{ (rad)}$
\begin{equation*}
\frac{\Delta \phi_1}{2} - \frac{\Delta \phi_2}{2}
\end{equation*}

\begin{equation*}
\frac{\Delta \theta^*}{\pi} = \frac{\Delta \phi^*}{2}
\end{equation*}

Both measurements prefer Mach-cone scenario.
forward-backward asymmetry

left-right asymmetry
$\gamma, \text{Jet}, \pi^0$ - hadron correlation

Comparisons are the most important!

Closer and closer to the initial parton energy

Gamma trigger

Jet (large R) trigger

Jet (small R) trigger

$\pi^0$ (hadron) trigger

more and more surface bias given by energy loss

2009/Sep/15, flow workshop, ECT* Trento
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J-cal for LHC-ALICE experiment
for back-to-back jets measurements

1 super module
=288 modules
$\Delta \eta \sim 0.7$
$\Delta \phi = 0.35$

4 towers/
module
Summary

1) **Gamma / Jet / hadron** triggered correlation analysis as a function of **centrality** and **R.P.** dependences gives us the QGP **tomography**.

2) **Mach-cone** and **Ridge** like shape w.r.t.
   a) geometrical **suppression** from energy loss,
   b) re-distribution of the lost energy,
   c) connection with **flow/expansion** dynamics
   d) transverse, longitudinal and radial(surface) direction

3) Low $p_T \, v_2$ can be biased by the triggered jet.
   associated particle $v_2^{\text{hard}} > \text{inclusive } v_2^{\text{all}} > \text{thermal } v_2^{\text{soft}}$

4) Global understanding of $R_{AA}, \, v_2$ from low $p_T$ (flow) to high $p_T$ (suppression), especially **soft-hard interplay** at middle $p_T$ region (jet without any flow subtraction?).
200GeV Au+Au -> h-h (run7) ($p_T^{\text{Trig}} = 2\sim4\text{GeV}/c$, $p_T^{\text{Asso}} = 1\sim2\text{GeV}/c$)

- **central : 0-20%**
- **mid-central : 20-50%**
- **peripheral : 50-93%**

$\phi_{\text{Asso.}} - \phi_{\text{Trig.}}$ (rad)

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Results on fitting parameters

Gauss function: $F(\text{height, mean, width})$

$F_{\text{Near}}(A_0, D_0, S_0) + F_{\text{Away}+}(A_+, D_+, S_+) + F_{\text{Away}_-}(A_-, D_-, S_-)
\mid \pi - D_+ \mid = \mid D_- - \pi \mid$, $S_+ = S_-$

0.5$(A_+ + A_-)$

$S_0$

$D_0$

$\phi_{\text{Trig.}} - \Phi_{\text{R.P.}}$ (rad)

$S_\pm$/

near side peak position
left/right asymmetry

away side shoulder height
left/right asymmetry

away side shoulder peak position

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$F_{\text{Near}}$

$F_{\text{Away}+}$

$F_{\text{Away}_-}$

in-plane

$\phi_{\text{Trig.}} - \Phi_{\text{R.P.}}$ $[-\pi/2, \pi/2]$
\begin{align*}
n_{\text{Trig}}/\text{eve} \text{ (soft)} &= 3 \\
n_{\text{Assoc}}/\text{eve} \text{ (soft)} &= 8 \\
n_{\text{Jet}}/\text{eve} \text{ (hard)} &= 1 \\
n_{\text{PTY}}/\text{jet} \text{ (hard)} &= 1.25 \\
v_{2,4}^{\text{Trig}} \text{ (soft)} &= 0.2, 0.029 \\
v_{2,4}^{\text{Assoc}} \text{ (soft)} &= 0.13, 0.010 \\
v_{2,4}^{\text{Jet}} \text{ (hard)} &= 0.0, 0.0 \\
v_{2,4}^{\text{PTY}} \text{ (hard)} &= 0.0, 0.0
\end{align*}

Simulation

\begin{align*}
\phi_{\text{ASSO}} - \phi_{\text{TRIG}} \text{ (rad)}
\end{align*}
AMPT (v1.11, parton cascade with string melting v2.11) Au+Au at $\sqrt{s_{NN}}=200\text{GeV}$

**Central vs Peripheral**

- $\phi_{\text{Trig.}} - \Phi_{\text{R.P.}} > 0$ (open symbols)
- $\phi_{\text{Trig.}} - \Phi_{\text{R.P.}} < 0$ (filled symbols)

**Phase Correlation Functions**

- **0~4%** $b = 0\sim3.5$ (fm)
- **4~18%** $b = 3.5\sim7$ (fm)
- **18~44%** $b = 7\sim10.5$ (fm)
- **44~%** $b = 10.5\sim$ (fm)

**Legend**

- Perfect R.P. resolution
- No $v_2$ subtraction needed

**True Reaction Plane**

- $\phi_{\text{Asso.}} - \phi_{\text{Trig.}}$ (rad) with trigger angle selected w.r.t. R.P.
- $p_T^{\text{Asso.}} : 0.5\sim1.5\text{GeV/c}$
- $p_T^{\text{Trig.}} : 1.5\sim5.0\text{GeV/c}$
AMPT (v1.25/v2.25 string melting) : Au+Au 200GeV b=7fm (with embedding option)

no embedding
7GeV in-plane
7GeV out-of-plane
7GeV at +45 deg
7GeV at −45 deg

mixed events with the same triggered (embedded) events
no embedding

7GeV in-plane

7GeV out-of-plane

7GeV at +45 deg

7GeV at −45 deg

mixed events without the triggered (embedded) events

--- mixed events from min.bias events ---
Direct $\gamma$ - hadron coincidence

QM09, M. Connors

Head Region $|\Delta \phi - \pi| < \pi/5$ rad

Direct $\gamma$-h
- $p+p \times 10$
- Run 7 Au+Au 0-20%

Global Scale Uncertainties:
- 13% $p+p$
- 16% Au+Au

Head region

Run 7 Au+Au 200GeV 9-12 x 3-5 GeV/c

Inclusive $\gamma$-h
- Decay $\gamma$-h
- Direct $\gamma$-h
Jet - hadron correlation

High Tower Trigger (HT) : \((\eta \times \phi) = (0.05 \times 0.05)\) \(E_T > 5.4\text{GeV}\)

RHIC-AGS’09, J. Putschke

Open symbols p+p
Di-jet simulation at 5.5TeV

between pythia (p+p) and pyquen (quench model)

D. Sakata, Grad. Student of Tsukuba

\[ \Delta \phi = \phi_{\text{JetAsso}} - \phi_{\text{JetTrig}} \text{(rad)} \]
Recoil $\gamma$-jet $E_{T}^{\gamma}>30$GeV

Recoil $\pi^{0}$-jet $E_{T}^{\pi^{0}}>30$GeV

Recoil Di-jet $E_{T}^{jet1}>70$GeV
Improvement in jet energy resolution