Recent jet correlation analysis at RHIC and LHC

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jet/photon suppression($R_{AA}$) / event anisotropy($v_2$)
particle/jet correlation($I_{AA}$) / geometrical dependence
mach-cone, ridge / soft-hard interplay
ridge in high mult. p+p events at LHC
Jet quenching
--- energy loss of parton in QGP ---
--- difference between hadron and direct photon ---

\[ R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{\text{binary}} \rangle_{AA}}{\text{Yield}_{pp}} \]

No energy loss for γ’s

Energy loss for quark and gluon jets (similar even for heavy quark)

\[ R_{AA} = \frac{\text{Yield}_{AA}}{\langle N_{\text{binary}} \rangle_{AA}} \]

Au+Au \( \sqrt{s_{NN}} = 200\text{GeV}, \) 0-10%

PHENIX preliminary

centrality 00-92 %

\[ p_T \] vs. \[ v_2 \]

PHENIX preliminary
Understanding of high $p_T \pi^0 v_2$ and $R_{AA}$ simultaneously

--- assumption of a common origin : energy loss ---

Models explaining measured $R_{AA}$ do not usually explain measured $v_2$. 

PRL105, 142301 (2010)
Two particle correlation (associate per trigger) 
--- two different features at low/high $p_T$ regions ---

\[ I_{AA} = \frac{(N^{ta}/N^t)_{Au+Au}}{(N^{ta}/N^t)_{p+p}} \]

$I_{AA}$ is slightly higher than $R_{AA}$ 
less suppressed than singles 
surface/tangential bias?

enhancement / suppression 
broadening / un-modified shape
Reaction plane (path length) dependent energy loss
--- one of dominant sources of $v_2$ at high $p_T$ ---

thickness dependence of penetration is more dominant than tangential surface emission.

QM04: STAR

arXiv:1010.1521

Au+Au 20-60%

$\pi^0$ $p_T = 4-7$ GeV/c
$h^+$ $p_T = 3-4$ GeV/c

$\phi_s = 0-15^\circ$
$\phi_s = 75-90^\circ$

$1/n^{\Delta \phi} dN_{jet}/d\Delta \phi$

$\Delta \phi$ (rad)

Au+Au 20-60%

$\pi^0$ $p_T = 4-7$ GeV/c
$h^+$ $p_T = 3-4$ GeV/c

$I_{AA}$

$\phi_s$ (rad)
Central Au+Au $\sqrt{s_{NN}}=200$ GeV  
STAR EMC + tracking data $E_T^{\text{jet}} \sim 21$ GeV

Central Pb+Pb $\sqrt{s_{NN}}=5.5$ TeV  
ALICE EMCal + tracking sim. $E_T^{\text{jet}} \sim 120$ GeV

Heavy Ion Cafe, 30/Oct/2010, Tokyo  
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**di-jet suppression**

![Di-jet suppression diagram](image)

Recoil Jet: $R=0.4$, $p_T^{cut}=2$ GeV/c vs $p_T^{cut}=0.2$ GeV/c

Trigger Jet: $p_T^{cut}=2$ GeV/c, $p_T^{(trig)}>20$ GeV/c

**single-jet suppression**

![Single-jet suppression diagram](image)

**PHENIX Preliminary**

Run-5 Cu + Cu at $\sqrt{s_{NN}} = 200$ GeV/c

Gaussian filter, $\sigma = 0.3$ vs. $\sigma = 0.4$

vs. $\pi^0$ (PRL 101, 162301)

0-20%  
$\sigma = 0.4$

$\sigma = 0.3$

Uncorrected Cu + Cu compared to embedded $p + p$

$\pi^0(z) = 0.7$

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**STAR Preliminary**

Au+Au and $p+p$ at $\sqrt{s_{NN}} = 200$ GeV/c

Au+Au: 10% most central

kt $R=0.4$

anti-kt $R=0.4$

kt $R=0.2$

anti-kt $R=0.2$

---

**Hard Probe 2010, Yue Shi Lai**

**Hard Probe 2010, E. Bruna**
γ, Jet, π₀ - hadron correlation
--- Comparisons are the most important! ---

cone size dependent jet suppression can be understood by recovering of energy loss with a larger cone.

can be used to give a controlled bias in analysis and in triggering.

Closer and closer to the initial parton energy

--- Comparisons are the most important! ---

more and more surface bias given by energy loss
\( \gamma \)-Triggered Away-side Correlations: Jet Fragmentation Function in p+p and Au+Au

\[ dN \Big/ dz_T = Ne^{-b \cdot z_T}, \quad Z_T = p_T^h / p_T^\gamma \]

- p+p: \( b = 6.89 \pm 0.64 \)
- Au+Au: \( b = 9.49 \pm 1.37 \)

I\( _{AA}^{\gamma\text{had}} \) is naively expected and confirmed. Slightly higher I\( _{AA}^{\pi\text{had}} \) from surface/tangential bias.
Jet - hadron correlation

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

STAR Preliminary
0-20% Au+Au

<table>
<thead>
<tr>
<th>0.2 &lt; (p_{t,\text{assoc}}) &lt; 1.0 GeV</th>
<th>1.0 &lt; (p_{t,\text{assoc}}) &lt; 2.5 GeV</th>
</tr>
</thead>
</table>

Open symbols p+p

RHIC-AGS’09, J. Putschke

\(p_{t,\text{assoc}} > 2.5\) GeV

Open symbols p+p

Hardprobe 2010, J. Putschke

Jet axis

Trigger jet

Assoc.
Back-to-back Jet Calorimeter for LHC-ALICE experiment

D-CAL upgrade

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

4 towers/module
φ_s = [0,1]π/8
φ_s = [1,2]π/8
φ_s = [2,3]π/8
φ_s = [3,4]π/8
φ_s = [-1,0]π/8
φ_s = [-3,-2]π/8
φ_s = [-2,-1]π/8
φ_s = [-4,-3]π/8

200GeV Au+Au -> h-h
mid-central : 20-50%
$p_T^{Trig}$=2~4GeV/c
$p_T^{Asso}$=1~2GeV/c

in-plane associate regions
relatively lower $p_T$ left/right trigger w.r.t. R.P.
left/right associate w.r.t. trigger
strong preference of associate particle emission towards the in-plane (thinner) direction
not significant but some reversed trend at out-of-plane

$\Delta \phi = \phi_{Asso.} - \phi_{Trig.}$ (rad)
the same data in polar plots (R.P. is x axis) --- associate distribution for a given trigger direction ---

200GeV Au+Au -> h-h (p_T^{Trig}=2~4GeV/c, p_T^{Asso}=1~2GeV/c)

out-of-plane trigger
3π/8 < |φ_{Trig} - φ_{R.P.}| < π/2

in-plane trigger
|φ_{Trig} - φ_{R.P.}| < π/8

averaged over all trigger angles

base line
Trigger angle

PHENIX preliminary
the same data in polar plots (R.P. is x axis) --- associate distribution for a given trigger direction ---

200GeV Au+Au -> h-h

(p_{T_{Trig}}=2\sim4GeV/c, p_{T_{Asso}}=1\sim2GeV/c)

<table>
<thead>
<tr>
<th>Trigger angle</th>
<th>PHENIX preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>in-plane trigger</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\phi_{Trig} - \phi_{R.P.}</td>
</tr>
<tr>
<td>out-of-plane trigger</td>
<td></td>
</tr>
<tr>
<td>$3\pi/8 &lt;</td>
<td>\phi_{Trig} - \phi_{R.P.}</td>
</tr>
</tbody>
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Heavy Ion Cafe, 30/Oct/2010, Tokyo

Shinlchi Esumi, Univ. of Tsukuba
Au+Au 20-60%, 3<p_T^{trig}<4, 1<p_T^{assoc}<2 GeV/c

STAR Preliminary

Heavy Ion Cafe, 30/Oct/2010, Tokyo

Shinichi Esumi, Univ. of Tsukuba

SQM09, F. Wang
Participant Triangularity

\[ \varepsilon_3 = \frac{\sqrt{\langle r^2 \cos(3\phi) \rangle^2 + \langle r^2 \sin(3\phi) \rangle^2}}{\langle r^2 \rangle} \]

Hard Probe 2010, G. Roland

R.P. dependence (left/right asymmetry) still holds
\[ v_3 \text{ in AMPT reflects } \varepsilon_3 \]

Provides extremely good description of \[ v_3/v_2 \text{ vs centrality for } p_T > 0.8 \text{ GeV data} \]
\[ \Delta \phi = \phi_{asso} - \phi_{trig} \]

\[ \Delta \eta = \eta_{asso} - \eta_{trig} \]
\[ \Delta \phi = \phi_{asso} - \phi_{trig} \]

PHENIX data analysis is in progress by Takahito Todoroki, STAR data analysis is about to start…
\[ \Delta \eta = \eta_{asso} - \eta_{trig} \]

pythia8 : Ryo Funato

- \( \eta_{trig} < 0 \)
- \( \eta_{trig} > 0 \)
(1) Away side of a back-to-back (b-t-b) jet is wider in $\eta$ than in $\phi$.

(2) If there are two parallel b-t-b jets, away side of one b-t-b jet can be near side of the another b-t-b jet.

(3) Suppression as well as modification of b-t-b jet would depend on relative angle w.r.t. almond geometry, we know this from $v_2$ measurement and believe this is the major source of $v_2$ at high $p_T$.

(4) Therefore, there should be inter b-t-b jets correlation give by the geometry from (3), this could make near side ridge like effect, especially if the effect (3) has shaper dependence than $v_2 (=\cos 2x)$.

(5) We always measure inclusive $v_2$, which includes the effect (3). Therefore any modification which could generates the elliptic anisotropy would be included in the measured $v_2$.

(6) We subtract BG contribution with this $v_2$ from (5) by maximizing BG contribution assuming zero jet yield at minimum at any d$\phi$.

(7) If near and away side jets overlap each other, this subtraction underestimates the jet yield and can change the extracted jet shape.

(8) If you extract angular dependence of jet w.r.t. R.P., the results will easily be affected by the choice of $v_2$ from (5).
$N_{\text{ch}} = 258 \quad dN_{\text{ch}}/d\eta \approx 65$
• Coverage up to $|\eta|<2.5$; extremely high granularity, due to the small cell size and high longitudinal segmentation, to keep low occupancy (~ a few%) also at LHC nominal luminosity.

• It is the largest Silicon Tracker ever built: Strips: 9.3M channels; Pixels: 66M channels. **Operational fractions:** strips 98.1%; pixel 98.3%
Level-1:
Require $E_T > 60$ GeV in calorimeters

High-Level trigger:
Count number of tracks with $p_T > 0.4$ GeV/$c$, $|\eta| < 2$, within $dz < 0.12$ cm of a single vertex with $z < 10$ cm.
Minimum Bias
no cut on multiplicity

(a) MinBias, $p_T > 0.1 \text{GeV}/c$

High multiplicity data set
and $N > 110$

(c) $N > 110$, $p_T > 0.1 \text{GeV}/c$

The peak is truncated
in both distributions

Back-to-back jet correlations enhanced in high multiplicity sample.
**Minimum Bias**
no cut on multiplicity

(b) MinBias, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

**High multiplicity data set**
and $N>110$

(d) $N>110$, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$

New “ridge-like” structure extending to large $\Delta\eta$ at $\Delta\phi \sim 0$
No $\delta \phi \sim 0$ structure in PYTHIA 8 at large $\delta \eta$
Same for Herwig++, madgraph, PYTHIA6
No ridge effect in these models (with the tunes used)

1<p_T<3GeV/c
“Ridge” maximal for highest multiplicity and $1 < p_T < 3$ GeV/c

CMS arXiv:1009.4122
Min-bias trigger vs high mult trigger

R(Δφ)

N=7k
N=8k
N=9k
N=10k, Trigger 70

1<p_T<2 GeV/c
|ζ|>2

R(Δφ)

N=110
1<p_T<2 GeV/c
|ζ|>2

Ridge is seen using min bias trigger + offline selection
No trigger bias seen from comparison of trigger paths

HLT 70 vs HLT 85 for N > 110

Pixel-only tracks
3 hits in pixel detector

"HighPurity" tracks
Pixel + Silicon Strip tracker

(Largely) independent code
Independent detectors
Also: Variation of tracking + vertexing parameters

Use ECAL "photon" signal
Mostly single photons from π^0's
No efficiency, and p_T, φ smearing corrections

N>110
1<p_T<3 GeV/c

CMS preliminary

R(Δφ)

N=110
1<p_T<3 GeV/c
|ζ|>2

Track-photon correlations

Photon-photon correlations
Qualitative confirmation
Independent detector, independent reconstruction
Select higher fraction of possible beam-gas or beam-scrapping events

Reject beam background by veto on fraction of low quality tracks

Compare different run periods (fraction of pileup varies by x4-5)

Change in pileup fraction by factor 2-4 has almost no effect on ridge signal

Correlate tracks from high multiplicity vertex with tracks from different collision (vertex) in same bunch crossing

No background or noise effects seen in cross-collision correlations

Compare different vertex regions (fraction of pile-up ~ dN/dx)

Pileup effects are suppressed due to excellent resolution

Track counting done with $\sigma_{dz}, \sigma_{dxy}$ of O(100\,\mu m)
p_{T}-inclusive two-particle angular correlations in Minimum Bias collisions

Pythia D6T
Ridge is seen at high multiplicity p+p(LHC)

Charged hadron correlations in CMS tracker (|η| < 2.4)

seen in Au+Au at RHIC, but not in Cu+Cu? remember a large $v_2$ in Cu+Cu at RHIC

$\varepsilon_{STD} \sim \varepsilon_{part} (Au+Au)$

$\varepsilon_{STD} \ll \varepsilon_{part} (Cu+Cu)$

long range correlation is also seen at ISR, SppS, Fermi lab.
consistent with CGC picture? what if there is $v2$ in p+p?
$3 \leq p_{\text{TRIG}} \leq 4.5 \text{ GeV/c}$

$1 + R(y, \phi)$ for associated particles with $p_{\text{T}} > 0.5 \text{ GeV/c}$

$R + 1 \approx \frac{\text{mean track density for high-}\mu_{\text{T}} \text{ events}}{\text{mean track density for minimum-bias events}}$
Summary

jet/photon suppression ($R_{AA}$) / event anisotropy ($v_2$)
particle/jet correlation ($I_{AA}$) / geometrical dependence
mach-cone, ridge / soft-hard interplay
ridge in high mult. p+p events at LHC