Conical emission: $p_T$ and system dependences of 3-particle correlation and the first result with identified protons from STAR

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MOTIVATION

For away side in di-hadron correlation in central Au+Au collisions at RHIC:

- Suppression due to jet quenching.
- Double-peak:
  - Mach-cone (to be discussed)
  - Čerenkov gluon radiation (to be discussed)
  - Large angle gluon radiation
    I. Vitev, PLB 630, 78 (2005)
    A. D. Polosa et al., PRC 75, 041901(2007)
  - Jet deflection
    Armesto, PRC 72, 064910 (2005)
    Charles B. Chiu et al., PRC 74, 064909 (2005)
  - ...

4 < p_T^{trig} < 6 GeV/c,
 p_T^{asso} > 2 GeV/c

3 < p_T^{trig} < 4 GeV/c,
 1.3 < p_T^{asso} < 1.8 GeV/c
CONICAL EMISSION THEORIES

• **Mach-cone:**
  • Shock waves excited by a *supersonic* parton.
  • Can be produced in different theories:
    • **Hydrodynamics**
      • H. Stöcker et al. (Nucl.Phys.A750:121,2005)
      • J. Casalderra-Solana et. al. (J.Phys.Conf.Ser. 27:22,2005)
    • **Colored plasma**
    • **AdS/CFT**

• **Čerenkov Gluon Radiation:**
  • Radiation of gluons by a *superluminal* parton.

• **Parton Cascade**
WHY 3-PARTICLE CORRELATION?

(a) di-jets

(b) deflected jets

(c) mach cone

\[ \Delta \phi_1 \]

\[ \Delta \phi_2 \]

\[ \pi \]

\[ 0 \]
BACKGROUND SUBTRACTION

An example: Au+Au 200 GeV (0-12%),
3 < p_{T}^{\text{Trig}} < 4 GeV/c and 1 < p_{T}^{\text{Asso}} < 2 GeV/c

(A): raw signal; (B): hard-soft background; (C): soft-soft background; (D): flow (v2) background; (E): flow (v4) background; (F): final signal.
A normalization factor is obtained by 3-particle ZYAM (Zero Yield At Minimum), i.e. the average of the lowest 10% data points is required to be zero.

**Systematic uncertainty from the normalization factor:**

**One end** from 2-particle ZYAM, **the other end** from 3-particle ZYAM at only one lowest data-point.

**Other systematic uncertainties:**

Flow correction, multiplicity fluctuation etc.
RESULTS: SYSTEM DEPENDENCE

\(3 < p_T^{\text{Trig}} < 4 \text{ GeV}/c \) and \(1 < p_T^{\text{Asso}} < 2 \text{ GeV}/c\)

\[ \Delta \phi \]

\[ \frac{1}{N} \text{d}N / \text{d} \Delta \phi_1 \Delta \phi_2 \]

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RESULTS: SYSTEM DEPENDENCE

(3 < \(p_T^{\text{Trig}}\) < 4 GeV/c and 1 < \(p_T^{\text{Asso}}\) < 2 GeV/c)

\(\Delta \phi_1\) \(\Delta \phi_2\) \(\Delta \phi_1\) \(\Delta \phi_2\)

p+p 200GeV d+Au 200GeV Au+Au 200GeV(50-80%) Au+Au 200GeV(30-50%) Au+Au 200GeV(10-30%) Au+Au 200GeV(0-12%)

\(\Delta \phi_1\) \(\Delta \phi_2\) \(\Delta \phi_1\) \(\Delta \phi_2\)

\(1/N_{\text{trig}} \frac{dN_{\text{triplet}}}{d\Delta \phi_1 d\Delta \phi_2}\)

• Di-jet picture in p+p and d+Au.
RESULTS: SYSTEM DEPENDENCE

\[ (3 < p_T^{\text{Trig}} < 4 \text{ GeV/c} \text{ and } 1 < p_T^{\text{Asso}} < 2 \text{ GeV/c}) \]

\[ \Delta \phi \]

\[ \Delta \phi \]

\[ \Delta \phi \]

\[ \Delta \phi \]

**Di-jet + conical emission in Au+Au.**
CENTRALITY DEPENDENCE of average yield from different regions

\(3 < p_T^{\text{Trig}} < 4 \text{ GeV/c} \) and \(1 < p_T^{\text{Asso}} < 2 \text{ GeV/c}\)

- the system size dependences of average yield in 0.7x0.7 squares centered on the different regions.
CENTRALITY DEPENDENCE of emission angle

\[(3 < p_{T^{\text{Trig}}} < 4 \text{ GeV/c} \text{ and } 1 < p_{T^{\text{Asso}}} < 2 \text{ GeV/c})\]

- constant dependence of cone angle on system size.

\[1.42 \pm 0.02\]
Cu+Cu vs Au+Au

(3 < \(p_T^{\text{Trig}}\) < 4 GeV/c and 1 < \(p_T^{\text{Asso}}\) < 2 GeV/c)

\[
\frac{1}{N_{\text{trig}}} \frac{dN_{\text{triplet}}}{d(\Delta\phi)}
\]

there seems to be some difference between Cu+Cu and Au+Au, which needs more further studies.
(2) \( p_{T^{asso}} \) DEPENDENCE

with \( 3 < p_{T^{Trig}} < 4 \) GeV/c

in Au+Au 200 GeV (0-12%)

\[ \Delta \phi \]

\[ 0.5 < p_{T^{asso}} < 0.75 \text{ GeV/c} \]

\[ 0.75 < p_{T^{asso}} < 1 \text{ GeV/c} \]

\[ 1 < p_{T^{asso}} < 1.5 \text{ GeV/c} \]

\[ 1.5 < p_{T^{asso}} < 2 \text{ GeV/c} \]

\[ 2 < p_{T^{asso}} < 3 \text{ GeV/c} \]

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\( p_T^{\text{Asso}} \) DEPENDENCE of emission angle

with \( 3 < p_T^{\text{Trig}} < 4 \) GeV/c

- \( p_T^{\text{Asso}} \)-independent cone angle, consistent the prediction of Mach-cone, and inconsistent with that of Čerenkov.

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Three-particle correlations with trigger particles of $3 < p_T^{\text{Trig}} < 4$ GeV/c (A), $4 < p_T^{\text{Trig}} < 6$ GeV/c (B) and $6 < p_T^{\text{Trig}} < 10$ GeV/c (C) and associated particles of $1 < p_T^{\text{Asso}} < 2$ GeV/c for Au+Au collisions (0-12%) at $\sqrt{s_{NN}} = 200$ GeV/c;
\( p_T^{\text{Trig}} \) DEPENDENCES of average yield from different regions and emission angle with \( 1 < p_T^{\text{asso}} < 2 \) GeV/c

- the average yield in 0.7x0.7 squares centered on different regions and cone angle as a function of \( p_T^{\text{Trig}} \) respectively.

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PARTICLE IDENTIFICATION

for PID 3-particle correlation
PID 3-PARTICLE CORRELATIONS

$h$-$pp$ and $h$-$\pi\pi$

- $2.5 < p_T^{\text{Trig}} < 10 \text{ GeV/c}$ and $0.7 < p_T^{\text{asso}} < 1.4 \text{ GeV/c}$ in Au+Au collisions (0-12%) at $\sqrt{s_{NN}} = 200\text{GeV}$.

- More statics needed.
the diagonal and off-diagonal projections of ‘h-pp’
the diagonal and off-diagonal projections of ‘h-pp’

the diagonal and off-diagonal projections of ‘h-ππ’ (scaled by $1/55$)

→ Needs more statistics.
**PID 3-PARTICLE CORRELATIONS**

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diagonal and off-diagonal projections

**Diagonal:**

\[
\frac{1}{N_{\text{trig}}} \frac{dN_{\text{triplet}}}{d\Delta\phi} \]

**Off-diagonal:**

\[
\frac{1}{N_{\text{trig}}} \frac{dN_{\text{triplet}}}{d\Delta\phi} \]

---

the diagonal and off-diagonal projections of **h-ππ** (2.5 < p_{T}^{\text{Trig}}< 10 GeV/c and 0.7 < p_{T}^{\text{Asso}} < 1.4 GeV/c)

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PID 3-PARTICLE CORRELATIONS

The diagonal and off-diagonal projections of ‘h-ππ’ (2.5 < $p_T^{\text{Trig}}$ < 10 GeV/c and 0.7 < $p_T^{\text{Asso}}$ < 1.4 GeV/c)

The diagonal and off-diagonal projections of ‘h-hh’ (3 < $p_T^{\text{Trig}}$ < 4 GeV/c and 0.75 < $p_T^{\text{Asso}}$ < 1.0 GeV/c + 1.0 < $p_T^{\text{Asso}}$ < 1.5 GeV/c)
CONCLUSIONS

(1) A systematic study of three-particle correlation vs system (size), $p_T^{\text{Asso}}$, and $p_T^{\text{Trig}}$.

(2) $p_T^{\text{Asso}}$-independent cone angle consistent with Mach-cone emission, inconsistent with Čerenkov radiation.

(3) New data from Cu+Cu, and identified ‘h-pp’ and ‘h-\(\pi\pi\)’ in central Au+Au.

(4) No significant difference observed between ‘h-pp’ and ‘h-\(\pi\pi\)’ in shape within systematic error.
Back up
Cu+Cu vs Au+Au

(3 < \(p_T^{\text{Trig}}\) < 4 GeV/c and 1 < \(p_T^{\text{Asso}}\) < 2 GeV/c)

\[ \frac{1}{N_{\text{trig}}} \frac{dN}{d\Delta\phi} \]

Cu+Cu 200GeV(0-10%)
\[ N_{\text{part}} \approx 98 \]

Au+Au 200GeV(0-12%)
\[ N_{\text{part}} \approx 326 \]

the off-diagonal projection of ‘h-hh’

the diagonal projection of ‘h-hh’
# Speed of sound in different phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Speed of Sound</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGP</td>
<td>$1/\sqrt{3} \ c = 0.58 \ c$</td>
</tr>
<tr>
<td>Mixed Phase</td>
<td>0</td>
</tr>
<tr>
<td>Resonance Gas</td>
<td>0.47 $\ c$</td>
</tr>
<tr>
<td>Exp. Data *</td>
<td>0.15 $\ c$</td>
</tr>
</tbody>
</table>

*Note: If $\theta^M=1.42$ rad and $\cos(\theta^M)=c_s/c$, then $c_s=0.15c$*
Mach-cone and flow

- Rapidity distribution and longitudinal flow affects the observed angle and width.
- Transverse flow affects shape of 3-particle correlation.
  - signal at \( \sim 1 \) GeV/c \( \sim 9 \)x larger if flow and shockwave aligned than if perpendicular.

\[
E \frac{d^3N}{d^3p} = \frac{g}{(2\pi)^3} \int d\sigma_\mu p^\mu \exp \left[ \frac{p^\mu (u^\text{flow}_\mu + u^\text{shock}_\mu) - \mu_i}{T_f} \right]
\]

Renk, Ruppert,
Prediction of emission angle from Čerenkov radiation

FIG. 5 (color online). Dependence of the Cherenkov angle on momentum of the emitted particle.
Mach-like structure is born in strong parton cascade process, and furthermore developed in hadronic rescattering process.

The problem of excessive correlation magnitude.
$\Delta \phi$ correlations from AMPT

$(3 < p_T^{\text{trigger}} < 6 \text{GeV/c}, 0.15 < p_T^{\text{assoc}} < 3 \text{GeV/c})$

- No splitting is seen on away side under the soft $p_T$ cut in default version (only with hadronic rescattering)! 

![Graph showing $\Delta \phi$ correlations with different conditions and data points representing STAR data and default versions with and without hadronic rescattering.]
Parton cascade effect on 2- and 3-particle correlations

1) Hadronic rescattering mechanism alone can not give big enough splitting parameters and correlation areas.

2) Parton cascade mechanism is essential for describing the splitting amplitude of experimental Mach-like structure.

3) Large energy loss in dense partonic medium.
Time Evolution of Mach-like Structures in melting AMPT model

At least a lifetime of partonic matter of 1.5 fm/c is needed for the birth of Mach-like structures for a 10mb set.
Partonic Mach-like Shock Wave

Melting AMPT model (central 0-10%)
$|y| < 1.0$, $(2.5-4.) \times (1.-2.5)$ GeV/c
without hadronic rescattering

Au+Au 200 GeV (0-10%)

Splitting parameter $d(r)$

Lifetime effects

nucl-th/0610088, G. L. Ma et al.