Collective dynamics in dijet+QGP-fluid system

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4th Joint Meeting of the Nuclear Physics Divisions of APS and JPS
Waikoloa, Hawaii, October 9th, 2014
QGP and Jets in Heavy Ion Collisions

- **Relativistic Hydrodynamics**
  - Description of space-time evolution of QGP

- **Jet Quenching**
  - Creation of high-energy partons (jets)
  - Energy loss of jets due to strong interactions with the medium
QGP and Jets in Heavy Ion Collisions

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  - Creation of high-energy partons (jets)
  - Energy loss of jets due to strong interactions with the medium
Where and how do the lost energies diffuse inside the medium?

- Relativistic Hydrodynamic Equations with Source Terms

\[ \partial_\mu T^{\mu\nu} = J^\nu \]

- Energy-momentum tensor of the QGP fluid
- Energy and momentum deposited from the jets

- Mach Cone
  - Interference of sound waves

Information about QGP’s properties and jet quenching
Energy Deposition into Fluid

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Observation of Dijet Events at LHC

Net-$p_T$ along the Strongly Quenched Jet

$$\rho_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{Leading Jet}})$$

$$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$$

$\Delta R < 0.8$  
$\Delta R > 0.8$

$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$

(Asymmetry Ratio)
Observation of Dijet Events at LHC

- **Net-** \( p_T \) along the Strongly Quenched Jet

\( \Delta R = 0.8 \)

\[
p_T^{||} = \sum_i -p_T^i \cos (\phi_i - \phi_{LeadingJet})
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**Net-** \( p_T \) along the Strongly Quenched Jet

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\[ \vec{p}_T^\parallel = \sum_i -p_T^i \cos(\phi_i - \phi_{Leading\,Jet}) \]

\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]

**Overall**

**In-Cone**

**Out-of-Cone**

\( \langle \vec{p}_T^\parallel \rangle \) GeV/c

\( p_{T1} - p_{T2} \)

\( p_{T1} + p_{T2} \)

\( A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} \)

(Asymmetry Ratio)

\( \Delta R < 0.8 \)

\( \Delta R > 0.8 \)

- > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

Christof Roland
(talk at QM2011)
Observation of Dijet Events at LHC

Net-$p_T$ along the Strongly Quenched Jet

$$\Delta R = 0.8$$

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Overall

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$$\Delta R < 0.8$$

$$\Delta R > 0.8$$

$$A_J = \frac{pT1 - pT2}{pT1 + pT2}$$

(Assymmetry Ratio)
Observation of Dijet Events at LHC

**Net-** $p_T$ along the Strongly Quenched Jet

$$\Delta R = 0.8$$

$$p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{LeadingJet}})$$

$$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$$

**Figure 15:** Average missing transverse momentum, for both centrality ranges and even for events with large observed dijet asymmetry, in both

- **Overall momentum balance of dijet events**

$$\int D L \ dt = 6.7$$

<table>
<thead>
<tr>
<th>In-Cone</th>
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<tbody>
<tr>
<td>Overall</td>
<td>0.1 0.2 0.3 0.4</td>
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**Asymmetry Ratio**

$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

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Net-$p_T$ along the Strongly Quenched Jet

$$\Delta R = 0.8$$

$$p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{LeadingJet})$$

$$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$$

Overall

<table>
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<td><img src="graph.png" alt="Graph" /></td>
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In-Cone

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Out-of-Cone

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Asymmetry Ratio

$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$
Observation of Dijet Events at LHC

Net-\( p_T \) along the Strongly Quenched Jet

\[
p_T^{||} = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{LeadingJet}})
\]

\[
\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}
\]

\( p_T \)

Overall

In-Cone

Out-of-Cone

\( \Delta R < 0.8 \)

\( \Delta R > 0.8 \)

\[
A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}
\]

(Asymmetry Ratio)
Observation of Dijet Events at LHC

Net-$p_T$ along the Strongly Quenched Jet

\[ p_T^\parallel = \sum_i -p_i^T \cos (\phi_i - \phi_{\text{Leading Jet}}) \]
\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]

Overall

In-Cone

Out-of-Cone

Low-$p_T$ Particles

\[ A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}} \]

(Asymmetry Ratio)
Observation of Dijet Events at LHC

- **Net-** $p_T$ along the Strongly Quenched Jet

$$ p_T^{\parallel} = \sum_i -p_T^i \cos (\phi_i - \phi_{Leading Jet}) $$

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Christof Roland (talk at QM2011)
Observation of Dijet Events at LHC

- **Net-** $p_T$ along the Strongly Quenched Jet

$p_T^{\parallel} = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{LeadingJet}})$

$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$

- Leading Jet $p_{T2}$
- Subleading Jet $p_{T1}$

<Christof Roland (talk at QM2011>
Observation of Dijet Events at LHC

Net-$p_T$ along the Strongly Quenched Jet

Subleading Jet $p_T1$

Leading Jet $p_T2$

CMS Preliminary

$\langle p_T^{||} \rangle = \sum_i -p_T^i \cos(\phi_i - \phi_{LeadingJet})$

$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$

Low-$p_T$ enhancement up to large $\Delta R$

$\phi > 0.5$

1.0 - 2.0

4.0 - 8.0

0.5 - 1.0

2.0 - 4.0

8.0 - 300.0
**Observation of Dijet Events at LHC**

- **Net-** $p_T$ along the Strongly Quenched Jet

$$p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{Leading Jet}})$$

$$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}$$

- **Leading Jet**
  - $p_{T1}$

- **Subleading Jet**
  - $p_{T2}$

- CMS

- Low-$p_T$ enhancement up to large $\Delta R$

- Originating from excited medium?

[Graph representing CMS data with color-coded regions indicating different $p_T$ values and $\Delta R$ ranges: 0.5 - 1.0, 1.0 - 2.0, 4.0 - 8.0, 8.0 - 300.0 with $\phi > 0.5$.]
Dijet + Expanding QGP-fluid System

Solve the hydro eqs. with source terms numerically **without linearization**

- **Dijets through an Expanding Fluid**
  - Ideal QGP-fluid in **(3+1)-D** Milne coordinate system $(\tau, x, y, \eta)$

- **Freeze-out**
  - Isothermal freezeout surface at $T_{fo} = 0.16$ GeV
  - Cooper-Frye formula
Yasuki Tachibana, "Collective dynamics in dijet+QGP-fluid system"

Dijet + Expanding QGP-fluid System

- Ideal QGP-fluid in \((3+1)\)-D Milne coordinate system \((\tau, x, y, \eta)\)

Solve the hydro eqs. with source terms numerically without linearization

Dijets through an Expanding Fluid

Freeze-out

- Isothermal freezeout surface at \(T_{fo} = 0.16\ \text{GeV}\)
- Cooper-Frye formula

Transverse plane \(\eta = 0\)

Reaction plane \(x = 0\ \text{fm}\)

Leading Jet \(p_T1\)

Subleading Jet \(p_T2\)

200 GeV

200 GeV

\(x\)

\(y\)
Momentum Flow in Dijet Event

- Net-$p_T$ along the sub-leading jet

\[
\langle p_T^{||} \rangle = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}}), \quad \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}
\]

Overall

\[
\langle p_T^{||} \rangle \text{ GeV/c}
\]

In-Cone

\[
\Delta R < 0.8
\]

Out-of-Cone

\[
\Delta R > 0.8
\]
Momentum Flow in Dijet Event

- Net-\(p_T\) along the sub-leading jet

\[
\langle p_T^{||} \rangle = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}}), \quad \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}
\]

![Diagram showing momentum flow in dijet event](image)

Overall

In-Cone \(\Delta R < 0.8\)

Out-of-Cone \(\Delta R > 0.8\)
Momentum Flow in Dijet Event

\[ \hat{\rho}_T^\parallel = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}}), \quad \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \]

\begin{align*}
\langle \hat{\rho}_T^\parallel \rangle \text{ GeV/c} \\
\text{vs} \Delta R \text{ GeV/c} \\
\end{align*}

Deposited energy transported by the collective flow upto large \( \Delta R \).
Yasuki Tachibana, "Collective dynamics in dijet+QGP-fluid system"

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Contribution of Medium Excited by Dijet

Only Contribution from Hydro (Jets are not included)

[Graph showing subleading and leading jet directions with corresponding differential distributions]
Contribution of Medium Excited by Dijet

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Leading jet direction

\[ \frac{d\langle p_T \rangle}{d\phi d\eta} \text{ GeV/c} \]

Subleading jet direction

\[ \frac{d\langle p_T \rangle}{d\phi d\eta} \text{ GeV/c} \]

\[ p_T > 8 \text{ GeV/c} \]

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Leading jet direction

Subleading jet direction

\[
\frac{d\langle p_T \rangle}{d\phi d\eta} \quad \text{GeV}/c
\]

\[
\frac{d\langle p_T \rangle}{d\phi d\eta} \quad \text{GeV}/c
\]

\[
4 \text{ GeV}/c < p_T < 8 \text{ GeV}/c
\]
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$\frac{d\langle p_T \rangle}{d\phi d\eta} \text{ GeV/c}$

Leading jet direction

Subleading jet direction

$2 \text{ GeV/c} < p_T < 4 \text{ GeV/c}$
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$\frac{d\langle p_T \rangle}{d\phi d\eta}$ GeV/$c$

Leading jet direction

Subleading jet direction

$1\,\text{GeV}/c < p_T < 2\,\text{GeV}/c$
Contribution of Medium Excited by Dijet

Only Contribution from Hydro (Jets are not included)

Leading jet direction

Subleading jet direction

\[
\frac{d \langle p_T \rangle}{d \phi d \eta} \text{ GeV/c}
\]

\[
\frac{d \langle p_T \rangle}{d \phi d \eta} \text{ GeV/c}
\]

0.5 GeV/c < \( p_T \) < 1 GeV/c
Contribution of Medium Excited by Dijet

Only Contribution from Hydro (Jets are not included)

Leading jet direction

Subleading jet direction

Lower- $p_T$  Broader in subleading direction
Contribution of Medium Excited by Dijet

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Leading jet direction

Subleading jet direction

Lower- $p_T$  →  Broader in subleading direction
Summary

- Collective response to jet propagation in QGP
  - Relativistic hydrodynamic equations with source terms

- A pair of jets traveling through an expanding fluid
  - Solve the equation numerically without linearization
  - Ideal fluid in full (3+1)-D Milne coordinate
  - Mach cones distorted by the expansion
  - Low-$p_T$ enhancement up to large angles from jet
$\frac{d\langle p_T \rangle}{d\phi d\eta}$ GeV/c

Leading jet direction

Subleading jet direction

$\frac{d\langle p_T \rangle}{d\phi d\eta}$ GeV/c
$\frac{d\langle p_T \rangle}{d\phi d\eta} \text{ GeV}/c$

Leading jet direction

Subleading jet direction

$\frac{d\langle p_T \rangle}{d\phi d\eta} \text{ GeV}/c$
$0.5 \text{ GeV}/c < p_T < 1 \text{ GeV}/c$