Di-jet asymmetric momentum transported by QGP fluid


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Outline

- Introduction
- Hydro Model with Source Terms
- Simulations and results
- Summary
Introduction
Di-jet asymmetry

- **Jet quenching**
  - Creation of high-energy partons (jets)
  - Energy loss of jets due to strong interactions with the medium

- **Observation of di-jet asymmetry**
  - Pair creations of jets
  - Energy difference between the observed jets

Christof Roland (talk at QM2011), modified
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\[ p_T > 8 \text{ GeV} \]
\[ 4 \text{ GeV} < p_T < 8 \text{ GeV} \]
\[ 1 \text{ GeV} < p_T < 4 \text{ GeV} \]
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Bjorken (1983), Gyulassy and Plumer (1990), Gyulassy and Wang (1994), ...

CMS (2011)

Subleading Jet \( p_T^2 \)

Leading Jet \( p_T^1 \)

![Jet quenching and di-jet asymmetry diagram](image)

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

Bjorken (1983), Gyulassy and Plumer (1990), Gyulassy and Wang (1994), ...

CMS (2011)

1 GeV < \( p_T < 4 \) GeV

4 GeV < \( p_T < 8 \) GeV

\( p_T > 8 \) GeV

Christof Roland (talk at QM2011), modified
Overall momentum balance of di-jet events

- Missing transverse momentum

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

Positive direction

Leading Jet

CMS (2011)

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S. Chatrchyan et al. [CMS Collaboration], Phys. Rev. C 84, 024906, modified

1, Introduction

Yasuki Tachibana, "Di-jet asymmetric momentum transported by QGP fluid"
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\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} = 0.8 \]

Figure 14: Average missing transverse momentum, for two centrality bins, 30–100% (left) and 0–30% (right). For the solid circles, values are shown as a function of di-jet momentum. The colored bands show the contribution to asymmetry, one sees that indeed...

\[ h_6 \]

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\[ = 0.8 \]

[Image: Overall momentum balance of di-jet events diagram]
Overall momentum balance of di-jet events

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Overall momentum balance of di-jet events

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Track of In-Cone

Track of Out-of-Cone
Overall momentum balance of di-jet events

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Overall momentum balance of di-jet events

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Low-\(p_T\) particles

Originated from the collective flow?
Hydro Model with Source Terms
QGP-Fluid + Jet Model

- Relativistic hydrodynamic equations with external sources
  - (3+1)-D perfect QGP-fluid
    \[ \partial_\mu T^{\mu\nu} = J^\nu \]
    - Energy-momentum tensor of the QGP fluid
    - Energy and momentum deposited from the jets
  - Massless jet particle traveling in a straight line
  - Collisional energy loss
    \[
    J^0(x) = \left[ -\frac{dp^0_{\text{jet}}}{dt} \right] \delta^{(3)}(x - x_{\text{jet}}(t))
    \]
    \[
    \mathbf{J}(x) = \frac{p_{\text{jet}}}{p^0_{\text{jet}}} J^0(x)
    \]

Solve this hydrodynamic equations numerically **without linearization**
Collective flow induced by 1-jet

- 1-jet traveling through a uniform fluid

**Energy density** \((t = 9\ \text{fm/c})\)

**Flow velocity** \((t = 9\ \text{fm/c})\)

- Mach cone structure
- Vortex ring around the passage

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Collective flow induced by 1-jet

- **1-jet traveling through a uniform fluid**

Energy density \((t = 9 \text{ fm/c})\) and Flow velocity \((t = 9 \text{ fm/c})\)

-Mach cone structure

Simulations and Results
A Pair of Jets Traveling through an Expanding Fluid

- Fluid expanding strongly in the longitudinal direction
  - (3+1)-D perfect QGP-fluid (PPM)
  - Expanding coordinate system
    \((\tau, x, y, \eta)\)
  - New scheme at high precision
  - Initial condition of the energy density
    \(\eta: \text{Flat} + \text{Gaussian}\)
    \(x, y: \text{Glauber model (Pb-Pb, central coll.)}\)

- Di-jet
  - Massless
  - Back to back same energy jets
  - Traveling straight in the plane \(\eta = 0\)
  - Collisional energy loss
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\[
A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}
\]
Expansion + induced flow

- Energy density distribution of the fluid in the x-y plane

\[ e \text{ [GeV}^4\text{]} \]

```
x [fm]  
-15  -10  -5   0   5   10  15  

y [fm]  
-15  -10  -5   0   5   10  15  
```
Expansion + induced flow

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$e \ [\text{GeV}^4]$
Expansion + induced flow

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\[ e \left[ \text{GeV}^4 \right] \]
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-15, -10, -5, 0, 5, 10, 15

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Expansion + induced flow

$E$ [GeV$^4$]

$e [\text{GeV}^4]$
Transverse momentum along the jets

- $p_T$-distribution of the particles originated from the collective flow (momenta of the jet particles are added to $p_T > 8$ GeV)

Christof Roland (talk at QM2011), modified
Missing transverse momentum

- Transverse momentum along the jets
  - $p_T$-distribution of the particles originated from the collective flow (momenta of the jet particles are added to $p_T > 8 \text{ GeV}$)

Deposited energy transported by the collective flow
Summary
Summary

- Relativistic hydrodynamic equations with source terms
  - Solve the equation numerically without linearization
  - Perfect fluid in full (3+1)-dimensional space
  - New scheme at high precision

- A pair of jets traveling through an expanding fluid
  - Mach cones distorted by the expansion
  - Many low-\(p_T\) particles in the out-of-cone region

Qualitative description of the CMS data

Deposited energy transported by the collective flow
back up
Outlook

- More realistic energy loss models
- Viscosity
- Event-by-event

.....
Energy loss

\[- \frac{dp^0_{jet}}{dt} = A \times \frac{8}{3} \pi \alpha_s^2 T^2 \left( 1 + \frac{1}{6} n_f \right) \log \frac{\sqrt{4T p^0_{jet}}}{m_D} \]
Cooper-Frye formula

\[
E \frac{dN}{d^3p} = \frac{dN}{p_T dp_T d\phi_p d\eta} = \int f(x, p) p^\mu d\sigma_\mu
\]

\[
f(x, p) = \frac{d}{(2\pi)^3} \frac{1}{\exp \left[ p^\mu u_\mu(x) / T(x) \right] + 1}
\]

At fixed \( \tau \),
\[
p^\mu d\sigma_\mu = \tau p_T \cosh (\eta_p - \eta) \, dx dy d\eta
\]

\[
\langle p_T \rangle = \int dp_T p_T \frac{dN}{dp_T}
\]

\[
= \int dp_T p^\mu d\sigma_\mu d\eta_p \, p_T^2 f(x, p)
\]
New scheme at high precision

- Relativistic hydrodynamic equations

\[ T^{\mu\nu};_{\mu} = 0. \]

Expanding (- expanding) coordinate system

\[
\frac{\partial}{\partial \tau} (\tau T^{\tau\beta}) + \frac{\partial}{\partial x} (\tau T^{x\beta}) + \frac{\partial}{\partial y} (\tau T^{y\beta}) + \frac{1}{\tau} \frac{\partial}{\partial \eta_s} (\tau T^{\eta_s\beta}) - \left( \frac{\partial}{\partial \eta_s} \Lambda^\beta_{\nu}(\eta_s) \right) T^{\eta_s\nu} = 0. 
\]

Additional source term

Nonconservation

New scheme

Lorentz transformation

time evolution

Expanding - Cartesian coordinate system

\[
\frac{\partial}{\partial \tau} (\tau T^{\tau\nu}) + \frac{\partial}{\partial x} (\tau T^{x\nu}) + \frac{\partial}{\partial y} (\tau T^{y\nu}) + \frac{\partial}{\partial \eta_s} (\tau T^{\eta_s\nu}) = 0. 
\]

Conservation

K. Murase, YT, M. Hongo, R. Kurita and T. Hirano