Emission of Low Momentum Particles at Large Angles from Jet

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Outline

- Introduction
- Hydrodynamic Model with a Source Term
- Simulations and Results
- Summary
Jet Quenching

- **Energy loss of high-energy partons**
  - Creation of high-energy partons (jets) at the same time as a QGP fluid
  - Energy loss of jets due to strong interactions with the medium
  - Extraction of QGP’s stopping power

- Pair creations of jets
  - Difference of energy loss between the pair particles due to position of the creation
  - Energy difference between the observed jets

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

From SCIENCE @ BERKELEY LAB.
Motivation

Jet quenching observed at LHC  CMS (2011)

Subleading Jet  $p_{T,2} > 50 \text{ GeV}$

Leading Jet  $p_{T,1} > 120 \text{ GeV}$

Large angle emission of low-$p_T$ particles  
(Necessary to balance the whole $p_T$)

Originated from the collective flow?

Purpose of the current study

Hydrodynamic Model with a Source Term

Study the dynamics of the QGP fluid induced by jets
Motivation

Jet quenching observed at LHC  CMS (2011)

Subleading Jet

$p_{T,2} > 50 \text{ GeV}$

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Purpose of the current study

Hydrodynamic Model with a Source Term

Study the dynamics of the QGP fluid induced by jets
Hydrodynamic Model with a Source Term
Hydrodynamic Equation with a Source Term

- Relativistic hydrodynamic equation
  - Energy-momentum conservation of the fluid
    \[ \partial_\mu T^{\mu\nu} = 0 \]
    \( T^{\mu\nu} \): energy-momentum tensor of the QGP fluid

- Relativistic hydrodynamic equation with a source term
  - Hydrodynamic equation with deposited energy and momentum
    \[ \partial_\mu T^{\mu\nu} = J^{\nu} \]
  \( J^{\nu} \): source term (Energy and momentum deposited by jets)

Solve this nonlinear equation numerically without linearization

Describe the dynamics of jets and the QGP fluid simultaneously
Source Term

Source term and energy loss

\[ J' ': \text{source term} \ (\text{Energy and momentum deposited by jets}) \]

Assume the sudden thermalization for the deposited energy and momentum

Jet energy loss mechanism

GLV, BDMPS-Z-ASW, AMY, Higher Twist, AdS/CFT, ....

In this study

The dynamics of the QGP fluid induced by jets

use a simple model as the jet energy loss
Source Term

### Energy-momentum conservation in the whole system

- Distribution functions of constituents of the fluid and jet particles
  \[
  f_h(x, p) : \text{fluid part} \quad f_j(x, p) : \text{jet part}
  \]

- Relativistic Boltzmann equation of jet particles
  \[
  p^\mu \partial_\mu f_j(x, p) = C_j[f_h, f_j] \quad C_j[f_h, f_j] : \text{Collision term}
  \]

- Energy-momentum tensors
  \[
  T_h^{\mu\nu}(x) = \int \frac{d^3p}{p^0} \ p^\mu p^\nu f_h(p, x) , \quad T_j^{\mu\nu}(x) = \int \frac{d^3p}{p^0} \ p^\mu p^\nu f_j(p, x)
  \]

- Energy-momentum conservation
  \[
  \partial_\mu \left[ T_h^{\mu\nu}(x) + T_j^{\mu\nu}(x) \right] = 0
  \]
Source Term

- Energy-momentum conservation in the whole system

- Distribution functions of constituents of the fluid and jet particles

\[ f_h(x, p) : \text{fluid part} \quad f_j(x, p) : \text{jet part} \]

- Relativistic Boltzmann equation of jet particles

\[ p^\mu \partial_\mu f_j(x, p) = C_j[f_h, f_j] \quad C_j[f_h, f_j] : \text{Collision term} \]

- Energy-momentum tensors

\[ T^{\mu\nu}_h(x) = \int \frac{d^3p}{p^0} p^\mu p^\nu f_h(p, x) \quad T^{\mu\nu}_j(x) = \int \frac{d^3p}{p^0} p^\mu p^\nu f_j(p, x) \]

- Energy-momentum conservation

\[ \partial_\mu \left[ T^{\mu\nu}_h(x) + T^{\mu\nu}_j(x) \right] = 0 \]
Assume constituents of the fluid are always in local equilibrium

- Energy-momentum conservation

\[ \partial_\mu T^\mu_\nu (x) = - \partial_\mu T^\mu_\nu (x) \]

- Source term

\[ J(x)^\nu \equiv - \partial_\mu T^\mu_\nu (x) \]

\[ = - \int \frac{d^3p}{p^0} p^\nu p^\mu \partial_\mu f_j (x, p) = - \int \frac{d^3p}{p^0} p^\nu C_j [f] \]

2-body → 2-body elastic scatterings between a jet and a constituent of the fluid

\[ J(x)^\nu = \int \frac{d^3p}{p^0} \frac{d^3p'}{p'^0} \frac{d^3k}{k^0} \frac{d^3k'}{k'^0} (p - p')^\nu w(p', k'|p, k) f_j (p, x) f_h (k, x) \]

\[ w(p', k'|p, k) : \text{transition rate} \]
Simulations and Results
3. Simulations and Results  

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**Settings**

- **Fluid**
  - Perfect QGP-fluid in full (3+1)-dimensional space
  - Massless, ideal gas EoS \( P(e) = \frac{1}{3} e \)

- **Source term**
  - Massless jet particle traveling in a straight line
  - Neglect the effect of the flow velocity on the energy loss

\[
J^0(x) = J^1(x) = \left[ -\frac{dp^0_{jet}(t)}{dt} \right] \delta(3)(x - x_{jet}(t))
\]

\[
J^2(x) = J^3(x) = 0
\]

- **Jet energy loss**

\[
- \frac{dp^0_{jet}(t)}{dt}
\]

- All particles are classical
- 2-body → 2-body elastic scatterings
- \( t \)-channel dominant, Debye mass cut-off
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Simulations

- **Test case**
  - 1-jet traveling through a uniform fluid
    - Flow induced by a jet particle

- **More realistic case**
  - A pair of jets traveling through an expanding fluid
    - Flow induced by jets
    - Radially expanding background
1-Jet Traveling through a Uniform Fluid

- Initial energy of the jet particle: \( E_0 = 50 \text{ GeV} \)
- Initial temperature of the fluid: \( T_0 = 0.5 \text{ GeV} \)
3. Simulations and Results

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1-Jet Traveling through a Uniform Fluid

- Initial energy of the jet particle: $E_0 = 50 \text{ GeV}$
- Initial temperature of the fluid: $T_0 = 0.5 \text{ GeV}$
1-Jet Traveling through a Uniform Fluid

- Peak at the position of the jet
- **Mach cone** structure
- Low energy density region inside the cone
1-Jet Traveling through a Uniform Fluid

- Flow velocity perpendicular to the cone
- Flow following the jet on the passage
- **Vortex ring** around the passage

3. Simulations and Results

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3. Simulations and Results

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1-Jet Traveling through a Uniform Fluid

- Flow velocity perpendicular to the cone
- Flow following the jet on the passage
- **Vortex ring** around the passage

Flow velocity

$$(t = 9 \text{ [fm]})$$

Flow velocity color map: energy density
3. Simulations and Results

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1-Jet Traveling through a Uniform Fluid

- Flow velocity perpendicular to the cone
- Flow following the jet on the passage
- Vortex ring around the passage

Flow velocity color map: energy density

(t = 9 [fm])
A Pair of Jets Traveling through an Expanding Fluid

- A pair of jets traveling through an expanding fluid
  - Initial condition of the energy density: 3D-Gauss + cut-off
  
  \[
e [\text{GeV}^4]
  \]

  \[
  x \,[\text{fm}], \quad y \,[\text{fm}],
  \]

  Initial temperature at the center of the fluid:

  \[T_0 = 0.5 \text{ GeV}\]

- Jet pair created at off central position

Back to back same energy jets
**A Pair of Jets Traveling through an Expanding Fluid**

- A pair of jets traveling through an expanding fluid
  - Initial condition of the energy density: 3D-Gauss + cut-off
    - Initial temperature at the center of the fluid: $T_0 = 0.5 \text{ GeV}$
  - Jet pair created at off central position

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

\[ x [\text{fm}] \]

\[ y [\text{fm}] \]

Subleading Jet

Leading Jet

$E_0 = 150 \text{ GeV}$

Back to back same energy jets
3. Simulations and Results

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A Pair of Jets Traveling through an Expanding Fluid

**Increase of momentum along the jets**

\[
\Delta p_i^\| = \sum_{p \in i} p^\| - \sum_{p \in i} p_{\text{no jet}}^\|
\]

\(p^\|\): momentum component of the jet direction  

\(\theta\) = high, middle, low

A Pair of Jets Traveling through an Expanding Fluid

3. Simulations and Results

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Increase of momentum along the jets

\[
\Delta p_i^\parallel \equiv \sum_{p \in i} p^\parallel - \sum_{p \in i} p^\parallel_{\text{no jet}}
\]

\( p^\parallel \): momentum component of the jet direction

\( i \) = high, middle, low

![Graph showing the increase of momentum along the jets with different jet categories highlighted.]

- high-\( p \)  \( p > 8 \text{ [GeV]} \)
- middle-\( p \)  \( 4 < p < 8 \text{ [GeV]} \)
- low-\( p \)  \( 0 < p < 4 \text{ [GeV]} \)
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A Pair of Jets Traveling through an Expanding Fluid

\[ \Delta p^\parallel_i \equiv \sum_{p \in i} p^\parallel - \sum_{p \in i} p^\parallel_{\text{no jet}} \]  

\( p^\parallel \): momentum component of the jet direction  
\( i = \text{high, middle, low} \)

- **high-\( p \)**  \( p > 8 \text{ [GeV]} \)
- **middle-\( p \)**  \( 4 < p < 8 \text{ [GeV]} \)
- **low-\( p \)**  \( 0 < p < 4 \text{ [GeV]} \)

Low momentum particles are dominant at large angles from the jet

Consistency with the CMS data
Summary
Summary

- Model building to describe the dynamics of jets and the QGP fluid simultaneously
  - Relativistic hydrodynamic equation with a source term
    \[ \partial_\mu T^{\mu\nu} = J^\nu \]
  - Perfect fluid in full (3+1)-dimensional space

- Results
  - 1-jet traveling through a uniform fluid
    - Mach cone structure
    - Vortex ring around the passage of the jet inside the cone
  - A pair of jets traveling through an expanding fluid
    - Low momentum particles are dominant at large angles from the jet

Qualitative description of the CMS data
Outlook

- more realistic energy loss models
- $\tau - \eta$ coordinates
- viscosity

.....
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Back up
Jet energy loss

\[- \frac{dq^0(t)}{dt} = A \frac{\alpha_s^2}{2\pi} T^2(x) \left[ (1 - \gamma_{\text{Euler}}) + \ln \frac{q^0(t)}{2\pi \alpha_s T(x)} \right] \]
Flow velocity

\[ y \,[\text{fm}] \]

\[ x \,[\text{fm}] \]

Back up