Hydrodynamic excitation by jets in the expanding QGP

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Outline

- Introduction
- Model
- Simulations and Results
- Summary
Introduction
QGP fluid and jet quenching

Hydrodynamic behavior

Space-time evolution of the QGP

Relativistic hydrodynamics

Jet quenching

Energy loss of jets due to strong interactions with the QGP

Bjorken (1983), Gyulassy and Plumer (1990), Gyulassy and Wang (1994), ...
Hydrodynamic response to jet

Mach cone

Shockwave induced by a supersonic moving source

\[ \theta_M = \arcsin \left( \frac{c_s}{v} \right), \quad v > c_s \]

Stoecker ('05), Casalderrey-Solana, Shuryak, Teaney ('05),…
Purpose of this study

- Mach cone as a hydrodynamic response
  - Fluidity of the bulk medium
  - Properties of QGP e.g. sound velocity, viscosity, stopping power, etc.

- Bulk dynamics of the QGP in jet events in HIC
  - Hydrodynamic response to jets in the expanding QGP
  - Consequent spectra of particles from the bulk medium
Model
Energy deposition into fluid

Hydrodynamic equations with external sources

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

Energy-momentum tensor of the QGP fluid

Energy and momentum deposited from the jets

Assumption

Instantaneous thermalization of deposited energy and momentum

\[ J^\mu(x) = - \sum_{\text{jet}} \frac{dp^\mu_{\text{jet}}}{dt} \delta^{(3)}(x - x_{\text{jet}}) \]  (pointlike jet)

Solve the equations numerically
Numerical calculation example

1-jet traveling through a uniform fluid

- Mach cone
- Fast flow following the jet
Numerical calculation example

1-jet traveling through a uniform fluid

- Mach cone
- Fast flow following the jet
Numerical calculation example

- 1-jet traveling through a uniform fluid

- Mach cone
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Numerical calculation example

1-jet traveling through a uniform fluid

- Mach cone
- Fast flow following the jet
Simulations and Results
Jet through an expanding QGP

Expanding QGP fluid

- (3+1)-D ideal fluid
- Milne coordinates \((\tau, x, y, \eta_s)\)
- lattice-QCD EoS \(S.\ Borsanyi \textit{et al.} \ (2014)\)
- Initial profile (Pb-Pb, central collision)
- Isothermal freezeout \(T_f = 145\ \text{MeV}\)

Gamma-Jet event

- Massless jet
- Traveling straight in the plane \(\eta_s = 0\)
- Energy loss \(\frac{dp^0_{\text{jet}}}{dt} = -\left(\frac{T(x_{\text{jet}}(t))}{T_0}\right)^3 \frac{dp^0_{\text{jet}}}{dt}\bigg|_0\), \(T > 160\ \text{MeV}\)

\[T_0 = 500\ \text{MeV}, \quad \frac{dp^0_{\text{jet}}}{dt}\bigg|_0 = 15\ \text{GeV/fm}\]
Spectra after hydro evolution

Increase of the particles from the medium

\[ \Delta \frac{dN_{\pi^{\pm}}}{d\phi d\eta} = \frac{dN_{\pi^{\pm}}}{d\phi d\eta} - \frac{dN_{\pi^{\pm}}}{d\phi d\eta} \bigg|_{\text{no jet}} \quad (p_T < 4 \text{ GeV}/c) \]

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)
Spectra after hydro evolution

- Increase of the particles from the medium

\[
\Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\text{no jet}} \quad (p_T < 4 \text{ GeV/c})
\]

Only contribution of particles from the medium (Jets are not included)

- Azimuthal-angle distribution (event averaged)
Spectra after hydro evolution

- Increase of the particles from the medium

\[
\Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \left. \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \right|_{\text{no jet}} \quad (p_T < 4 \text{ GeV}/c)
\]

- Azimuthal-angle distribution (event averaged)

Only contribution of particles from the medium (Jets are not included)
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\]

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)

\( p_{T_{\text{jet}}} > 80 \text{ GeV}/c \)

(No energy loss)
Spectra after hydro evolution

Increase of the particles from the medium

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\text{no jet}} \quad (p_T < 4 \text{ GeV/c}) \]

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)

![Diagram showing azimuthal-angle distribution](image)

(No energy loss)
Spectra after hydro evolution

Increase of the particles from the medium

\[
\Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\text{no jet}} \quad (p_T < 4 \text{ GeV/c})
\]

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)

\[\Delta dN_{\pi^\pm}/d\phi d\eta|_{\eta=0} \]

\[p_{T_{\text{jet}}} > 80 \text{ GeV/c} \]

\[\text{full} \]

Spectra after hydro evolution

Increase of the particles from the medium

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\text{no jet}} \quad (p_T < 4 \text{ GeV/c}) \]

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)

\[ \Delta dN_{\pi^\pm} / d\phi d\eta \bigg|_{\eta=0} \]

\[ p_{T,\text{jet}} > 80 \text{ GeV/c} \]

Spectra after hydro evolution

Increase of the particles from the medium

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \left. \frac{dN_{\pi^\pm}}{d\phi d\eta} \right|_{\text{no jet}} \quad (p_T < 4 \text{ GeV}/c) \]

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)

\[ \Delta dN_{\pi^\pm} / d\phi d\eta \bigg|_{\eta=0} \]

- \( p_{T_{\text{jet}}} > 80 \text{ GeV}/c \)

\( p_{T_{\text{jet}}} \) jet > 80 GeV/c

\( p_{T_{\text{jet}}} < 4 \text{ GeV}/c \)

- full
Spectra after hydro evolution

Increase of the particles from the medium

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\text{no jet}} \quad (p_T < 4 \text{ GeV/c}) \]

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)
Spectra after hydro evolution

- Increase of the particles from the medium

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{no\ jet} \]  

\( (p_T < 4\text{ GeV/c}) \)

Only contribution of particles from the medium (Jets are not included)

- Azimuthal-angle distribution (event averaged)

\[ \frac{\Delta dN_{\pi^\pm}}{d\phi d\eta} \big|_{\eta=0} \]

\( p_{T,jet} > 80\text{ GeV/c} \)

\( p_T < 4\text{ GeV/c} \)

Spectra after hydro evolution

Increase of the particles from the medium

\[
\Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta}_{\text{no jet}} \quad (p_T < 4 \text{ GeV/c})
\]

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)

\[\Delta dN_{\pi^\pm} / d\phi d\eta \big|_{\eta=0} = 0\]

\[p_T^{\text{jet}} > 80 \text{ GeV/c}\]

Spectra after hydro evolution

Increase of the particles from the medium

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\text{no jet}} \]  
\( p_T < 4 \text{ GeV/c} \)

Only contribution of particles from the medium (Jets are not included)

Azimuthal-angle distribution (event averaged)

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\eta=0} \]

\( p_{T_{\text{jet}}} > 80 \text{ GeV/c} \)

Azimuthal-angle distribution (Event by Event)

Position of jet creation:

\[(x_0, y_0) = (3 \text{ fm}, -3 \text{ fm})\]
Interplay between Mach cone and radial expansion

Radial Flow

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} \]

\[ \eta \quad -\pi/2 \quad 0 \quad \pi/2 \quad \pi \quad 3\pi/2 \]

\[ \phi \]

\[ \Delta dN_{\pi^\pm}/d\phi d\eta|_{\eta=0} \]

\[ \pm \quad 0 \quad 0.5 \quad 1 \quad 1.5 \]

\[ -\pi/2 \quad 0 \quad \pi/2 \quad \pi \quad 3\pi/2 \]

Interplay between Mach cone and radial expansion

\[ \frac{dN_{\pi^\pm}}{d\phi d\eta} \]

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} \mid_{\eta=0} \]

Interplay between Mach cone and radial expansion

Push back by Mach cone

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} \]

\[ \frac{\Delta dN_{\pi^\pm}}{d\phi d\eta}|_{\eta=0} \]

Interplay between Mach cone and radial expansion

Yasuki Tachibana, "Hydrodynamic excitation by jets in the expanding QGP," Hard Probes 2015, McGill University, 30 June 2015, 30 June 2015
Interplay between Mach cone and radial expansion

Radial Flow

Push back by Mach cone

Interplay between Mach cone and radial expansion

Push back by Mach cone

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Interplay between Mach cone and radial expansion

Push back by Mach cone

Interplay between Mach cone and radial expansion

Radial Flow

Push back by Mach cone

$\Delta \frac{dN_{\pi^+} \pm}{d\phi d\eta}$

$e (GeV/fm^3)$

Interplay between Mach cone and radial expansion

Radial Flow

Push back by Mach cone

Interplay between Mach cone and radial expansion

Interplay between Mach cone and radial expansion

Interplay between Mach cone and radial expansion

Interplay between Mach cone and radial expansion

Interplay between Mach cone and radial expansion

Push back by Mach cone

Interplay between Mach cone and radial expansion

Push back by Mach cone

Direct signal of hydrodynamic response to jet including the information about the jet passage in medium
Summary
Summary

Hydrodynamic response to jet propagation in QGP

**Mach cone**
- Fluidity of the bulk medium
- Properties of QGP

Hydrodynamic equations with external sources

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

Interplay between Mach cone and radial expansion

Decrease of the number of particles due to the push back by Mach cone

- Direct signal of hydrodynamic response to jet propagation
- Information about the jet path in the medium
Back up
Azimuthal-angle distribution (Event by Event)

Position of jet creation:

\[(x_0, y_0) = (-3 \text{ fm}, 0 \text{ fm})\]
Event by Event initial condition
Event by Event initial condition
Event by Event initial condition