Interplay between Mach cone and radial expansion in jet events

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QGP fluid and jet quenching

- **QGP fluid**
  
  Bjorken (1983), ...
  
  Space-time evolution of the bulk QGP

- **Jet quenching**
  
  Bjorken (1983), Gyulassy and Plumer (1990), Gyulassy and Wang (1994), ...
  
  Energy loss of jets due to strong interactions with the QGP
Hydrodynamic response to jet quenching

- Mach cone

\[ \theta_M = \arcsin \frac{c_s}{v}, \quad v > c_s \]

Energy-momentum transport in the QGP fluid

- Influence on the observables
  - Low-\( p_T \) enhancement away from the jets
  - Jet structure inside the jet cone
    - (fragmentation function, transverse profile)

Tan Luo’s talk (this session)
Daniel Pablos’s talk (Tuesday)
Hydrodynamic response to jet quenching

• Mach cone

Stoecker ('05), Casalderrey-Solana, Shuryak, Teaney ('05),...

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  ![](image)

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- **Influence on the observables**
  
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  YT, Hirano ('12)

  YT, Hirano ('14)

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Hydrodynamic response to jet quenching

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Tan Luo’s talk (this session)
Daniel Pablos’s talk (Tuesday)
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
QGP fluid + jet model

Energy and momentum incoming to the QGP fluid

Hydrodynamic equations with source terms

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

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

Assumption
Instantaneous thermalization of deposited energy and momentum

\[ J^\mu (x) = - \frac{dp_{\text{jet}}^\mu}{dt} \delta^{(3)} (x - x_{\text{jet}}(t)) \]

- Hydrodynamic response to jet
- Background expansion
- Interplay between them
A jet traveling through the expanding QGP

• Gamma-jet events in central Pb-Pb collisions
  - (3+1)-D ideal hydro
  - Optical Glauber model, lattice EoS
  - Energy loss \[ \frac{dp^0_{jet}}{dt} = - \left[ \frac{T(x_{jet})}{T_0} \right]^3 \frac{dE}{dl} \bigg|_0 \]
    \[ \frac{dE}{dl} \bigg|_0 = 15 \text{ GeV/fm} \]
    \[ T_0 = 500 \text{ MeV} \]

• Mach cone developing in the expanding medium

![Diagram showing Mach cone development](image)

e.g.) Jet produced at \( (x_0, y_0) = (3.0 \text{ fm}, -3.0 \text{ fm}) \)
A jet traveling through the expanding QGP

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![Diagram showing energy distribution](image)
A jet traveling through the expanding QGP

- Gamma-jet events in central Pb-Pb collisions
  - (3+1)-D ideal hydro
  - Optical Glauber model, lattice EoS
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    \frac{dp_{\text{jet}}^0}{dt} = - \left[ \frac{T(x_{\text{jet}})}{T_0} \right]^3 \left. \frac{dE}{dl} \right|_0 = \frac{T_0}{500}\text{MeV} \quad \left. \frac{dE}{dl} \right|_0 = 15\text{ GeV/fm}^3
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\[e(x, y) = \text{expression}\]

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\[
\begin{align*}
  e(x_0, y_0) &= (3.0 \text{ fm}, -3.0 \text{ fm})
\end{align*}
\]
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  - Energy loss \( \frac{dp^0_{jet}}{dt} = - \left[ \frac{T(x_{jet})}{T_0} \right]^3 \frac{dE}{dl} \bigg|_0 \)
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\[ e \text{ (GeV/fm}^3) \]

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\[ \text{e.g.) Jet produced at} \quad (x_0, y_0) = (3.0 \text{ fm}, -3.0 \text{ fm}) \]
Spectra after hydro evolution

- Increase of the particles from the medium

\[
\Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta}_{\text{w/o jet}} \quad (1 < p_T < 2 \text{ GeV/c})
\]

- Azimuthal-angle distribution

Particles from jet fragmentation are not included

Event-averaged $p_T, \text{jet} > 80 \text{ GeV/c}$
Spectra after hydro evolution

- Increase of the particles from the medium

\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\text{w/o jet}} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\text{w/o jet}} \]  \hspace{1cm} (1 < p_T < 2\,\text{GeV/c})

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Single event $x_{\Gamma,\text{jet}}(\tau = 0) = (3\,\text{fm}, -3\,\text{fm})$
Spectra after hydro evolution

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  \text{(1 < } p_T < 2 \text{ GeV/c)}
  \]

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\[ y \]
\[
\Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\phi=0} = \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\phi=0} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{\phi=0} \\
\text{Event-averaged} \\
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\]

\[ x \]
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  (1 < p_T < 2 GeV/c)

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- Azimuthal-angle distribution

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

Event-averaged:
- $p_T,_{jet} > 80$ GeV/c

Single event:
- $x_{T, jet}(\tau = 0) = (3 \text{ fm}, -3 \text{ fm})$
Spectra after hydro evolution

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\[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \frac{dN_{\pi^\pm}}{d\phi d\eta} \bigg|_{w/o \ jet} \quad (1 < p_T < 2 \text{ GeV/c}) \]

Particles from jet fragmentation are not included

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Event-averaged
\[ p_T, \text{jet} > 80 \text{ GeV/c} \]

Single event
\[ \vec{x}_{\text{jet}}(\tau = 0) = (3 \text{ fm}, -3 \text{ fm}) \]

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

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

\( \phi \)
Spectra after hydro evolution

- Increase of the particles from the medium
  \[ \Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \lim_{w/o \text{ jet}} \frac{dN_{\pi^\pm}}{d\phi d\eta} \quad (1 < p_T < 2 \text{ GeV/c}) \]

- Azimuthal-angle distribution

Particles from jet fragmentation are not included.

Interplay between the Mach cone and the radial flow
Constraint on the jet path

- Trigger for photon
  - Extract small energy-loss events
- Jet production point distribution

<table>
<thead>
<tr>
<th>No trigger for photon</th>
<th>$p_{T,\text{jet}} \geq 80\text{GeV/c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event Fraction</td>
<td>0.0002 0.0006 0.001 0.0012 0.0014</td>
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<tr>
<th>$p_{T,\gamma} 110-120 \text{GeV/c}$</th>
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Yasuki Tachibana, Quark Matter 2015, Kobe, Japan, 28 September 2015
Constraint on the jet path

- Azimuthal-angle distribution for small energy-loss events
Constraint on the jet path

- Azimuthal-angle distribution for small energy-loss events

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

\[p_{T,\gamma} \text{ 110-120 GeV}/c\]

\[a) \ p_{T,\text{jet}} 100-110 \text{ GeV}/c\]

\[b) \ p_{T,\text{jet}} 110-120 \text{ GeV}/c\]
Summary

- Mach cone as hydrodynamic response to jet quenching
- Hydrodynamic equations with source terms
  Jet + expanding QGP fluid
- Interplay between Mach cone and radial expansion
  Decrease of the number of particles due to the push back by Mach cone

Direct signal of the Mach cone
Information about the jet path in the medium
Constraint on the jet path
Trigger also for photon in gamma-jet events