Collective flow induced by energetic partons in heavy-ion collisions


Yasuki Tachibana
Department of Physics, The University of Tokyo
Collaborator: Tetsufumi Hirano (Sophia Univ.)
26th Heavy Ion Cafe, 19 July 2014
Introduction
Jet Quenching

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

High-$p_T$ suppression

Extraction of QGP’s stopping power
Di-jet asymmetry

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

Christof Roland (talk at QM2011), modified
**Observation of di-jet asymmetry**

- Pair creations of jets
- Energy difference between the observed jets

Christof Roland (talk at QM2011), modified
Di-jet asymmetry

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

CMS (2011)

Subleading Jet $p_T^2$

Leading Jet $p_T^1$

$p_T > 8$ GeV

$4$ GeV < $p_T$ < $8$ GeV

$1$ GeV < $p_T$ < $4$ GeV

Christof Roland (talk at QM2011), modified
**Di-jet asymmetry**

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

---

*Christof Roland (talk at QM2011), modified*

- Red: \( p_T > 8 \text{ GeV} \)
- Green: \( 4 \text{ GeV} < p_T < 8 \text{ GeV} \)
- Yellow: \( 1 \text{ GeV} < p_T < 4 \text{ GeV} \)
- **Observation of di-jet asymmetry**
  - Pair creations of jets
  - Energy difference between the observed jets

![Di-jet asymmetry diagram](image)

**Legend**
- $p_T > 8$ GeV
- $4$ GeV < $p_T$ < $8$ GeV
- $1$ GeV < $p_T$ < $4$ GeV

Christof Roland (talk at QM2011), modified
**Di-jet asymmetry**

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

![Di-jet asymmetry diagram]

**Asymmetry ratio**

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

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

Color codes:
- Red: $p_T > 8$ GeV
- Green: $4$ GeV $< p_T < 8$ GeV
- Yellow: $1$ GeV $< p_T < 4$ GeV

Christof Roland (talk at QM2011), modified

---

26th Heavy Ion Cafe, 19 July 2014
Di-jet asymmetry

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

Asymmetry ratio

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

Where and how do the lost energies diffuse inside the medium?
Overall Momentum Balance

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

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

Positive direction

Leading Jet

Christof Roland (talk at QM2011), modified

---

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

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

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

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

\[
= 0.8
\]

Positive direction

Leading Jet

Christof Roland (talk at QM2011), modified

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

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

\[
\vec{\Psi}_T^{||} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}})
\]

\[
\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} = 0.8
\]

Positive direction

Leading Jet

Figure 14: Average missing transverse momentum, \( p_T^{\text{miss}} \) for 0–30% centrality, inside (\( \Delta R < 0.8 \)) the leading and subleading jet cones (right). For the solid circles, one sees that indeed the detected activity in the event due to instrumental (e.g. gaps or inefficiencies in the calorimeter) or physics (e.g. neutrino production) effects.
Overall Momentum Balance

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

$$
\psi_T^{|1|} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Leading Jet}})
$$

CMS (2011)

![Diagram](image)

Positive direction

Leading Jet

$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} = 0.8$

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

Christof Roland (talk at QM2011), modified

---

26th Heavy Ion Cafe, 19 July 2014

Yasuki Tachibana, "Collective flow induced by energetic partons in heavy-ion collisions"
Overall Momentum Balance

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

\[ \vec{\eta}_{T} = \sum \frac{p^i_T \cos(\phi_i - \phi_{Leading \, Jet})}{i} \]

\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} = 0.8 \]

Positive direction

Leading Jet

---

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

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

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

CMS (2011)

\[ \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} = 0.8 \]

Positive direction

Leading Jet

Christof Roland (talk at QM2011), modified

---

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

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

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

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

$= 0.8$

Positive direction

Leading Jet

Christof Roland (talk at QM2011), modified

26th Heavy Ion Cafe, 19 July 2014
Energy deposition in fluid

- **Mach cone**
  - interference of sound waves induced by the supersonic source

- Conical shock wave in the QGP-fluid

Energy deposition in fluid

- **Mach cone**
  - interference of sound waves induced by the supersonic source

- Conical shock wave in the QGP-fluid

Hydro Model with Source Terms
QGP-Fluid

- Relativistic hydrodynamic equations

\[ \partial_\mu T^{\mu\nu} = 0 \]

Energy-momentum tensor of the QGP fluid

Energy-momentum conservation inside the fluid

Initial state → Energy Stopping → Hard Collisions → Hydrodynamic Evolution → Hadron Freezeout

QGP-Fluid + Jet Model

- Relativistic 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

Assume instantaneously deposition and thermalization in fluid

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

\[ \mathbf{J}(x) = \frac{p^0_\text{jet}}{p^0_\text{jet}} J^0(x) \]

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

- 1-jet traveling through a uniform fluid

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

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

\[ \text{flow velocity} \quad e \quad (\text{GeV/fm}^3) \]

- Mach cone structure
- Vortex ring around the passage

Collective flow induced by 1-jet

- 1-jet traveling through a uniform fluid

\[ \begin{align*}
\text{flow velocity } & \quad e \ (\text{GeV/fm}^3) \\
\end{align*} \]

![Diagram showing collective flow induced by 1-jet](image)

- Mach cone structure
- Vortex ring around the passage

Collective flow induced by 1-jet

- 1-jet traveling through a uniform fluid

- Mach cone structure
- Vortex ring around the passage

Collective flow induced by 1-jet

- 1-jet traveling through a uniform fluid

Flow velocity $e$ (GeV/fm$^3$)

Mach cone structure
Vortex ring around the passage

Collective flow induced by 1-jet

- 1-jet traveling through a uniform fluid

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
    \(\eta: \text{Flat} + \text{Gaussian}\)
    \(x, y: \text{Glauber model} (Pb-Pb, \text{central coll.})\)

- Di-jet
  - Massless
  - Back to back same energy jets
  - Traveling straight in the plane \(\eta = 0\)
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
    $\eta$: Flat + Gaussian
    $x, y$: Glauber model (Pb-Pb, central coll.)

- Di-jet
  - Massless
  - Back to back same energy jets
  - Traveling straight in the plane $\eta = 0$
Expansion + induced flow
Expansion + induced flow

transverse plane

$\eta_s = 0$

$T \text{ (GeV)}$

0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0.05
0

$X \text{ (fm)}$

$Y \text{ (fm)}$
Yasuki Tachibana, "Collective flow induced by energetic partons in heavy-ion collisions"

Expansion + induced flow

reaction plane

\[ y = 0 \]

\[ T \text{ (GeV)} \]

\[ \begin{align*}
0.5 & \quad 0.45 \\
0.4 & \quad 0.35 \\
0.3 & \quad 0.25 \\
0.2 & \quad 0.15 \\
0.1 & \quad 0.05 \\
0 & \quad 0
\end{align*} \]

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

\[ \eta_s \]

26th Heavy Ion Cafe, 19 July 2014
Expansion + induced flow

reaction plane

\[ y = 0 \]

\[ T(\text{GeV}) \]

\[ 0 \quad 0.05 \quad 0.1 \quad 0.15 \quad 0.2 \quad 0.25 \quad 0.3 \quad 0.35 \quad 0.4 \quad 0.45 \quad 0.5 \]

\[ 0 \quad -5 \quad -10 \quad -15 \]

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

\[ 0 \quad 5 \quad 10 \quad 15 \]

\[ \eta_s \]
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 $p_T > 8$ GeV)

  ![Diagram showing missing transverse momentum distribution](image)

  Overall
  
  $p_T > (\text{GeV/c})$
  
  $A_J$

  $\Delta R < 0.8$

  $\Delta R > 0.8$

  Out-of-Cone

  $p_T$
  
  0-0.5[GeV]
  
  0.5-1[GeV]
  
  1-2[GeV]
  
  2-4[GeV]
  
  4-8[GeV]
  
  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 $p_T > 8$ GeV)

Deposited energy transported by the collective flow

Christof Roland (talk at QM2011), modified
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
Backup
Low-$p_T$ enhancement

$\Delta R$ -dependence  CMS (2014)

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

 CMS-PAS-HIN-14-010, modified

$p_{T,1}>120, p_{T,2}>50$ GeV/c

$|\eta_1|, |\eta_2|<0.5, \Delta \phi_{1,2}>5\pi/6$

anti-$k_T$ Calo R=0.3

$A_J>0.22, |h_{trk}|<2.4$

$p_{T,\text{trk}}$ (GeV/c):

- 0.5 - 1.0
- 2.0 - 4.0
- 1.0 - 2.0
- 4.0 - 8.0
- $>0.5$
- 8.0 - 300.0

low-$p_T$ enhancement upto large $\Delta R$

PP  5.3 pb$^{-1}$

CMS Preliminary

PbPb  0-30 %

$\sqrt{s_{NN}}=2.76$ TeV

Christof Roland (talk at QM2011), modified

26th Heavy Ion Cafe, 19 July 2014
Outlook

- Various jet energy loss models

- EoS
  - sound velocity

- Viscous hydro
  - transport coefficients (shear viscosity, …)

New approaches to extract the property of the QGP
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

New scheme

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

Nonconservation

K. Murase, YT in preparation

Lorentz transformation

time evolution

PPM

26th Heavy Ion Cafe, 19 July 2014
Energy loss

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

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

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

At fixed \( \tau \),

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

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

\[
= \int dp_T p^\mu d\sigma_\mu d\eta_p \, p_T^2 f(x, p)
\]