Jet quenching and medium response

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Outline

• Introduction
• Models
• Observables
• Summary
Jet propagation in the QGP medium

Jet-medium interaction

- Jet energy loss: Energy propagated outside the jet cone. (Different from parton energy loss)

- Medium response: some medium constituents get excited by the jet.

Leading paton

Medium induced radiation

Recoiled parton (Jet induced medium excitation)

Initial thermal parton (diffusion wake)
Where does the lost energy go?

- The energy and momentum deposited by the jet shower into the medium appear at large angles away from the jet axis.
Thermalization & Propagation

- Thermalization: How does the deposited energy thermalize?
- Propagation: How does the deposited energy propagate?
Background

- What are in the background of a reconstructed jet?
- Part of the medium background is correlated with jet (inside and outside the jet cone).
Parton energy loss in QGP

• Jet weakly coupled to the medium
  pQCD based calculation (BDMPS-Z, GLV, AMY, HT, SCETG)
  (LBT, MARTINI, QPYTHIA, JEWEL, YaJEM, .......)

• Jet strongly coupled to the medium
  AdS/CFT (HYBRID)
Jet quenching models with medium response

- JEWEL [BDMPS-Z]: recoiled partons transported. \(\text{(modified parton shower)}\)
- LBT [HT]: recoiled partons transported. \(\text{(shower + transport)}\)
- MARTINI [AMY]: recoiled partons transported. \(\text{(shower + transport)}\)
- CoLBT-hydro [HT]: Transport + Hydro parallel simulation. \(\text{(shower + transport)}\)
- Hybrid [AdS/CFT]: fully thermalized wake. \(\text{(modified parton shower)}\)
- Coupled Jet-Fluid [HT]: solve Boltzmann equation + Hydro simulation
- EPOS3-HQ: YaJEM + Hydro parallel simulation. \(\text{(modified parton shower)}\)
Jet quenching models with medium response

**JETSCAPE**

- **modified parton shower + transport**

- **Recoil-medium rescattering**
- **Energy momentum deposition into Hydro**

**Particle scattering for both medium and jet**

- **AMPT**
- **BAMPS**

- Linearized viscous hydrodynamics with source
A Linear Boltzmann Transport (LBT) Model

**Parton shower**
- Pythia
- Sherpa

**Jet propagation**
\[ p_1 \cdot \partial f_i (x_i, p_i) = E_1 (C_{\text{elastic}} + C_{\text{inelastic}}) \]
- Rescattering
  - Shower-thermal & recoil-thermal
- Back reaction
  - Track the initial thermal parton

**Local medium information** $\varepsilon \, T \, u$

**Initial profile**
- AMPT
- TRENTO

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

**Hadronic observables**

**Fragmentation**

**Recombination**

**No feedback**
A coupled LBT Hydro (CoLBT-hydro) Model

**Parton shower**
- Pythia
- Sherpa

**Jet propagation**
\[ p_1 \cdot \partial f_i (x_i, p_i) = E_1 (C_{\text{elastic}} + C_{\text{inelastic}}) \]
- Rescattering
  - Shower-thermal & recoil-thermal
  - Parton above \( P_{\text{cut}} \)

**Fragmentation**

**Recombination**

**Real time feedback**
- Local medium information \( \varepsilon T u \)

**Hadronic observables**

**Initial profile**
- AMPT
- TRENTO

**Medium evolution**
\[ \partial_{\mu} T^{\mu\nu} = j^{\nu} \]
- Source term
  - Parton below \( P_{\text{cut}} \)
- Negative source
  - Initial thermal parton

**Cooper Frye**

**LBT**
- Hard

**CLvisc**
- Soft
Jet induced medium response

- **Structure of medium response**
  Hydro: Mach cone as hydro response.
  Transport: Mach cone like structure.

- **Diffusion wake**
  Unique structure of medium response

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**CoLBT-hydro**  
Chen et al, Phys.Lett. B777 86-90

**Jet-Fluid**  
Tachibana, Chang, Qin, PRC 95, 044909

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**EPOS3-HQ**  
Iurii Karpenko HP2018
Jet induced medium response

- Structure of medium response in $\eta$-$\phi$ plane.
- A naive picture of jet induced medium response.

Energy propagated to large open angle and a negative wake in the back direction.
Particle recoil vs Hydro response

MATTER + LBT (w/ Recoil)

\[ E_{\text{dep}} = 1 \text{ GeV for brick} \]
\[ E_{\text{dep}} = 2 \text{ GeV for expanding} \]

- Not much difference in brick.
- Difference in an expanding medium.
- Fluid plays very important roles in energy diffusion process.
Single jet suppression

- The cone size dependence is quantitatively depended on jet energy loss.
- Energy recovered at large angle via the inclusion of medium response.

LBT
Y. He et al, 1809.02525 (2018)

anti-$k_t$, \( s = 5.02 \text{ TeV} \)
LBT Pb+Pb 0 - 10 %
\(|y| < 2.1\)

JEWEL
R. K. Elayavalli, K. C. Zapp, JHEP 1707, 141

Jet-Fluid
Tachibana, Chang, Qin, PRC 95, 044909
Single jet suppression

- Smaller cone size dependence → slower energy recovery.

Hydro response?

- Background subtraction.

\[ \frac{\rho_E(\theta)}{\rho_E(\theta)} \]

\[ 500 < p_T^{\text{jet}} < 1000 \text{ GeV} \]

\[ \text{anti}-k_T, |n_\text{jet}| < 2 \]

0-10%
Jet shape (inside jet cone)

**LBT** Luo et al, arXiv:1803.06785

**HYBRID** JHEP 1803 010 (2018)

**Jet-Fluid** Tachibana, Chang, Qin, PRC 95, 044909

**JEWEL** R. K. Elayavalli, K. C. Zapp, JHEP 1707, 141

**MARTINI** C. Park, S. Jeon, C. Gale ('18)
Jet shape (outside jet cone)

- Energy lost by the hard parton is transported out of the jet cone by soft particles.
- Medium response to jet generally lead to enhancement at large angle.

Jet-Fluid
Tachibana, Chang, Qin, PRC 95, 044909

LBT
Luo, Cao, He, Wang, arXiv:1803.06785

MARTINI
C. Park, S. Jeon, C. Gale ('18)
• Energy is recovered at large angles in the form of soft particles.
• Adding medium response is essential for a full understanding of jet quenching.
γ-hadron correlations (back direction)

- A broaden peak at small $p_T$ range.
- Suppression of hadron yield at small $p_T$ range in the near side due to diffusion wake.

The effect of the diffusion wake could be observed by looking at leading jet suppression in dijet events with different rapidity configuration.
Jet mass

- Decrease by jet quenching.
- Increase by including medium response.

\[
m^2 = \left( \sum_{i \in \text{jet}} p_i^{\mu} \right)^2
\]

MARTINI C. Park, S. Jeon, C. Gale (’18)

Pb-Pb @ 2.76TeV 0-10%

\[60 < p_T^{\text{jet}} < 80 \text{GeV/c}\]
\[80 < p_T^{\text{jet}} < 100 \text{GeV/c}\]
\[100 < p_T^{\text{jet}} < 120 \text{GeV/c}\]

JEWEL K. C. Zapp’s talk at EMMI RRTF
R. K. Elayavalli, K. C. Zapp, JHEP 1707, 141
Jet mass

- Decrease by jet quenching.
- Increase by including medium response.

\[ m^2 = \left( \sum_{i \in jet} p_i^\mu \right)^2 \]

HYBRID Casalderrey, Milhano, Pablos, Rajagopal arXiv:1907.11248

Daniel Pablos: Wednesday
Groomed jet mass

- Enhancement of the large mass range.
- The rise in large mass tail is caused by medium response in JEWEL, LBT and Hybrid.

\[
\frac{M_g}{p_T^{jet}} = \sqrt{(E_1 + E_2)^2 - (\bar{p}_1 + \bar{p}_2)^2} / p_T^{jet}
\]
Particle ratio inside jet

- Strange baryon-to-meson ratio in jet increases at intermediate pT range in Pb-Pb collisions.

- Sensitive to the deposition energy cut $p_{cut}^0$ between hard and soft.
Summary

• To achieve a consistent description of jet-medium interactions with total energy momentum conservation we need to include the jet induced medium response.

• Two ways for the implementation of medium response. (Particle recoil vs Hydro response)

• Medium response effect in various jet observables especially on the enhancement of the soft particles at the large angle around jets.
Summary

- What do we learn?

  - Unique identification of medium response effect in jet
    Diffusion wake, Particle ratio inside the jet
Outlook

- Intermediate pT range

- Searching for Mach Cone

![Graph showing R_AA as a function of p_T](image)

![Diagram showing y fm vs x fm with T GeV color scale](image)
Outlook

- Jet interference

- Searching in phase space with jet grooming


Jet tools 2017, Jet tools 2019, EMMI RRTF
Outlook

- JETSCAPE: “Framework” of Event Generator for heavy ion collisions
Thanks
\( \gamma \)-hadron correlations

- The suppression of high pT hadrons
  \textbf{LBT:} hard parton energy loss

- The enhancement of soft hadrons at small pT
  \textbf{Hydro:} medium excitation

- With increasing pT-gamma transition point from suppression to relative enhancement shifts to larger \( \xi \).

- This transition point corresponds to a fixed pT range.

\[
I_{AA}(z) = \frac{D_{AA}(z)}{D_{pp}(z)} \quad z = \frac{p_T^h}{p_T^\gamma}
\]

\[
\xi = \log \frac{1}{z}
\]
Jet splitting function

- Some theoretical calculation suggest that the data prefer coherent energy loss.

- The MC calculation show that the inclusion of the recoil (medium response) will lead to stronger modification of the groomed jet splitting function.
Backup

Molly Taylor: Wednesday

CMS Preliminary

\[ R_{AA} \]

\[ 
\text{anti-}k_t, \ R = 0.4 \text{ jets} \\
\text{LBT } \sqrt{s_{NN}} = 5.02 \text{ TeV} \\
\text{ATLAS } \sqrt{s_{NN}} = 5.02 \text{ TeV} \\
\text{ATLAS } \sqrt{s_{NN}} = 2.76 \text{ TeV} \\
\text{red} \\
\text{blue} \\
\text{ATLAS} \\
\text{LBT} \\
\text{LYL} < 2.1 \\
0-10\% \\

\[ R_{AA} \]

\[ 
\text{MARTINI} \\
\text{LBT w/ showers only} \\
\text{LBT w/ med. response} \\
\text{HYBRID w/ wake} \\
\text{HYBRID w/o wake} \\
\text{HYBRID w/ pos wake} \\
\]

\[ p_T^{jet} (\text{GeV}) \]

\[ 200 \quad 500 \quad 800 \quad 1000 \]
Single jet suppression

- Effect of medium response (black vs red)

- Effect of diffusion wake (red vs blue)

\[
R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}^{jet}/d\eta_p dp_T^{jet}}{d^2N_{pp}^{jet}/d\eta_p dp_T^{jet}}
\]