Flow excited by full jet shower in QGP fluid and its effect on jet shape

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Jet quenching in QGP medium

- Jet in heavy ion colls.
  - produced in initial hard scattering
  - propagating through QGP medium
- QGP medium effect

J. D. Bjorken (1983), M. Gyulassy, M. Plumer (1990), M. Gyulassy, X.-N. Wang (1994), ...
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- QGP medium effect
  - interaction with medium constituents
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Jet energy loss
Modification of jet structure

J. D. Bjorken (1983), M. Gyulassy, M. Plumer (1990), M. Gyulassy, X.-N. Wang (1994), ...
Medium response to jet quenching

H. Stöcker ('05), J. Casalderrey-Solana, E. Shuryak, D. Teaney ('05),…

- Energy-momentum deposition
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- Energy-momentum deposition
  - induced flow in QGP fluid

Medium response to jet quenching

- Energy-momentum deposition
  - induced flow in QGP fluid

Enhancement of particle emission from medium
Medium response to jet quenching


- Energy-momentum deposition
  - induced flow in QGP fluid

Further modification

Jet energy loss
Modification of jet structure
Motivation

• Purpose
  - Flow induced as medium response to jet shower
  - Medium contribution to jet energy loss and shape

• Method
  - Describe both jet shower and medium evolution
  - Interaction between them

Jet shower transport equation

+ Hydrodynamic equation with source term

• Other works about jet with medium response

Linearized Boltzmann Transport (LBT) Model

LBT + Hydro Model

T. Luo (Saturday), SS. Cao (Saturday)

W. Chen (Saturday)

Hybrid Strong/Weak Coupling Model by D. Pablos (Saturday), JEWEL by R. Kunnawalkam Elayavalli (Saturday), Multi-phase Transport Model by G.-L. Ma (Saturday), Linearized Hydro w/ Source Term by A. Ayala (Sunday)
Full jet shower evolution


- Transport equations for all partons in jet shower
  - evolution of energy and transverse momentum distributions, $f_j(\omega_j, k_{j\perp}^2, t)$
    ($j$: parton species)

\[
\frac{df_j(\omega_j, k_{j\perp}^2, t)}{dt} = \hat{e}_j \frac{\partial f_j(\omega_j, k_{j\perp}^2, t)}{\partial \omega_j} + \frac{1}{4} \hat{q}_j \nabla_{k_{\perp}}^2 f_j(\omega_j, k_{j\perp}^2, t) + \sum_i \int d\omega_i dk_{i\perp}^2 \left[ \frac{d\tilde{\Gamma}_{i\rightarrow j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2)}{d\omega_j d^2k_{j\perp} dt} f_i(\omega_i, k_{i\perp}^2, t) - \frac{d\tilde{\Gamma}_{j\rightarrow i}(\omega_j, k_{j\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i d^2k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t) \right]
\]

\[
\hat{e}_j = \frac{\hat{q}_j}{4T}
\]

\[
\frac{d\tilde{\Gamma}_{j\rightarrow i}(\omega_i, k_{i\perp}^2 | \omega_j, 0)}{d\omega_i dk_{i\perp}^2 dt} = \frac{2\alpha_s}{\pi} \frac{xP_{j\rightarrow i}(x)\hat{q}_j(t)}{\omega k_{i\perp}^4} \sin^2 \left( \frac{t - t_0}{2\tau_f} \right)
\]

($P_{j\rightarrow i}(x = \omega_j/\omega_i)$: vacuum splitting function)

Initial jet profiles are generated by PYTHIA

Full jet shower evolution


- Transport equations for all partons in jet shower
  - evolution of energy and transverse momentum distributions, $f_j(\omega_j, k_{j\perp}^2, t)$ ($j$: parton species)

$$\frac{df_j(\omega_j, k_{j\perp}^2, t)}{dt} = \hat{e}_j \frac{\partial f_j(\omega_j, k_{j\perp}^2, t)}{\partial \omega_j} \text{ collisional energy loss}$$

$$(\text{longitudinal})$$

$$+ \frac{1}{4} \hat{q}_j \nabla^2_{k_{\perp}} f_j(\omega_j, k_{j\perp}^2, t) \text{ momentum broadening}$$

$$(\text{transverse})$$

$$+ \sum_i \int d\omega_i dk_{i\perp}^2 \left[ \frac{d\hat{\Gamma}_{i\rightarrow j}(\omega_i, k_{i\perp}^2|\omega_i, k_{i\perp}^2)}{d\omega_i d^2k_{i\perp} dt} f_i(\omega_i, k_{i\perp}^2, t) - \frac{d\hat{\Gamma}_{j\rightarrow i}(\omega_i, k_{i\perp}^2|\omega_j, k_{j\perp}^2)}{d\omega_i d^2k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t) \right]$$

$$\hat{e}_j = \frac{\hat{q}_j}{4T}$$

$$\frac{d\hat{\Gamma}_{j\rightarrow i}(\omega_i, k_{i\perp}^2|\omega_j, 0)}{d\omega_i dk_{i\perp}^2 dt} = \frac{2\alpha_s x P_{j\rightarrow i}(x) \hat{q}_j(t)}{\pi} \omega k_{i\perp}^4 \sin^2 \left( \frac{t - t_0}{2\tau_f} \right)$$

$$(P_{j\rightarrow i}(x = \omega_j/\omega_i): \text{vacuum splitting function})$$

Initial jet profiles are generated by PYTHIA

N.-B. Chang (NEXT talk)
Full jet shower evolution


- Transport equations for all partons in jet shower
  - evolution of energy and transverse momentum distributions, \( f_j(\omega_j, k_{j\perp}^2, t) \)

\[
\frac{df_j(\omega_j, k_{j\perp}^2, t)}{dt} = \hat{e}_j \frac{\partial f_j(\omega_j, k_{j\perp}^2, t)}{\partial \omega_j} - \frac{1}{4} \hat{q}_j \nabla_{k_{\perp}}^2 f_j(\omega_j, k_{j\perp}^2, t)
\]

\[
\sum_i \int d\omega_i dk_{i\perp}^2 \left[ \frac{d\tilde{\Gamma}_{i\rightarrow j}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_j d^2k_{j\perp} dt} f_i(\omega_i, k_{i\perp}^2, t) - \frac{d\tilde{\Gamma}_{j\rightarrow i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i d^2k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t) \right]
\]

- Interaction with medium constituents
  - collisional energy loss (longitudinal)
  - momentum broadening (transverse)
  - medium-induced radiation

\[
\hat{e}_j = \frac{\hat{q}_j}{4T}
\]

\[
\frac{d\tilde{\Gamma}_{j\rightarrow i}(\omega_i, k_{i\perp}^2 | \omega_j, 0)}{d\omega_i dk_{i\perp}^2 dt} = \frac{2\alpha_s}{\pi} \frac{xP_{j\rightarrow i}(x)q_j(t)}{\omega k_{i\perp}^4} \sin^2 \left( \frac{t - t_0}{2\tau_f} \right)
\]

\( (P_{j\rightarrow i}(x = \omega_j/\omega_i): \text{vacuum splitting function}) \)

Initial jet profiles are generated by PYTHIA

Space-time evolution of QGP medium

- **Hydrodynamic equation with source term**
  
  - describe hydrodynamic response to jet and background expansion

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

  - Energy-momentum tensor of the QGP fluid
  - Energy and momentum deposited from the jet

- **Source term**

  \[
  J^\nu(x) = \sum_j \int \frac{d\omega_j dk_j^2}{2\pi} \frac{d\phi_j}{d\omega_j} k_j^\nu \left. \frac{df_j(\omega_j, k_j^2)}{dt} \right|_{\hat{e}, \hat{q}} \delta^{(3)}(x - x_j(k, t))
  \]

  - momentum transfer between medium and jet

  \[
  \frac{df_j(\omega_j, k_j^2)}{dt} \bigg|_{\hat{e}, \hat{q}} = \left( \hat{e}_j \frac{\partial}{\partial \omega_j} + \frac{1}{4} \hat{q}_j \nabla_{k_\perp}^2 \right) f_j(\omega_j, k_j^2, t)
  \]

  \[
  x_j(k, t) = x_{0\text{jet}} + \frac{k_j}{\omega_j} t
  \]

**Assumption**

Instantaneous local thermalization of deposited energy and momentum
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

\[ \tau = 0.9 \text{ fm/c} \quad e \text{ (GeV/fm}^3) \]

Initial jet energy: 120 GeV

 deposited momentum

jet direction

\[ \tau^2 = (\hat{\phi}_p - \hat{\phi}_{jet})^2 + (\eta_p - \eta_{jet})^2 \]

jet energy distribution

change of jet energy

Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

\[ \tau = 1.2 \text{ fm/c} \quad \epsilon \text{ (GeV/fm}^3\text{)} \]

Initial jet energy: 120 GeV

Jet energy distribution

Change of jet energy
Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

\[ \tau = 1.5 \text{ fm/c} \quad e \text{ (GeV/fm}^3) \]

\[ \tau = \sqrt{(\phi_p - \phi_{jet})^2 + (\eta_p - \eta_{jet})^2} \]

medium energy density

Initial jet energy: 120 GeV

jet energy distribution

change of jet energy

Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

\[
\tau = 1.8 \text{ fm}/c \quad e \quad (\text{GeV}/\text{fm}^3)
\]

\[
\tau = \sqrt{(\phi_p - \phi_{\text{jet}})^2 + (\eta_p - \eta_{\text{jet}})^2}
\]

- Initial jet energy: 120 GeV
- Deposited momentum
- Jet energy distribution
- Change of jet energy
Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

![Diagram showing medium energy density and jet energy distribution](image)

\[ \tau = 2.1 \text{ fm/c} \quad e \text{ (GeV/fm}^3) \]

- medium energy density
- deposited momentum
- change of jet energy

**Initial jet energy:** 120 GeV

**Jet energy distribution**

**Present** vs. **Previous**

**Jet direction**

$\tau = \sqrt{(\phi_p - \phi_{jet})^2 + (\eta_p - \eta_{jet})^2}$
Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

\[ \tau = 2.4 \text{ fm/c} \quad e \quad (\text{GeV/fm}^3) \]

Initial jet energy: 120 GeV

Jet energy distribution

Change of jet energy

Jet direction

$\tau = \sqrt{(\phi_p - \phi_{\text{jet}})^2 + (\eta_p - \eta_{\text{jet}})^2}$
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

\[ \tau = 2.7 \text{ fm/c} \quad e \quad (\text{GeV/fm}^3) \]

\[ \tau = \sqrt{(\phi_p - \phi_{\text{jet}})^2 + (\eta_p - \eta_{\text{jet}})^2} \]

Initial jet energy: 120 GeV

Jet energy distribution

Change of jet energy

Medium energy density

Deposited momentum
Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

\[ \tau = 3 \text{ fm/c} \quad \quad e \quad \text{(GeV/fm}^3\text{)} \]

\[ \tau = \sqrt{(\phi_p - \phi_{jet})^2 + (\eta_p - \eta_{jet})^2} \]

Initial jet energy: 120 GeV

Jet energy distribution

Change of jet energy

Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

![Diagram of medium energy density and jet energy distribution](image)

- $\tau = 3.3$ fm/$c$
- Initial jet energy: 120 GeV
- Deposited momentum
- Change of jet energy
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

medium energy density

$$\tau = 3.6 \text{ fm/c}$$

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

Initial jet energy: 120 GeV

jet energy distribution

change of jet energy
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

\[ \tau = 3.9 \text{ fm/c} \quad e \quad (\text{GeV/fm}^3) \]

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medium energy density
```

```
jet direction
\]

```
jet energy distribution
```

```
change of jet energy
```

```
Initial jet energy: 120 GeV
```

Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD
- Evolution of medium and jet shower

\[ \tau = 4.2 \text{ fm/c} \quad e \text{ (GeV/fm}^3\text{)} \]

\[ \tau = \sqrt{(\phi_p - \phi_{\text{jet}})^2 + (\eta_p - \eta_{\text{jet}})^2} \]

\[ \Delta(dE_j/d\tau) \text{ (GeV)} \]

Initial jet energy: 120 GeV

jet direction

medium energy density

deposited momentum

jet energy distribution

change of jet energy

Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

\[
\tau = 4.5 \text{ fm/c} \quad e (\text{GeV/fm}^3)
\]

Initial jet energy: 120 GeV

Jet energy distribution

Change of jet energy

Medium energy density
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

$\tau = 4.8$ fm/c  $e$ (GeV/fm$^3$)

Initial jet energy: 120 GeV

Jet energy distribution

Change of jet energy
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

\[
\tau = 5.1 \text{ fm/c} \quad e \text{ (GeV/fm}^3\text{)}
\]

- medium energy density

- deposited momentum

- jet direction

\[
\tau = \sqrt{(\phi_p - \phi_{\text{jet}})^2 + (\eta_p - \eta_{\text{jet}})^2}
\]

- jet energy distribution

- change of jet energy

Initial jet energy: 120 GeV
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

\[ \tau = 5.4 \text{ fm/c} \quad e \text{ (GeV/fm}^3\text{)} \]

\[ \tau = \sqrt{(\phi_p - \phi_{jet})^2 + (\eta_p - \eta_{jet})^2} \]

Initial jet energy: 120 GeV

Jet energy distribution

Change of jet energy
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

\[ \tau = 5.7 \text{ fm/c} \quad e \text{ (GeV/fm}^3\text{)} \]

\[ \tau = \sqrt{(\phi_p - \phi_\text{jet})^2 + (\eta_p - \eta_\text{jet})^2} \]

medium energy density

jet direction

Evolution of medium and jet shower

jet energy distribution

change of jet energy

Initial jet energy: 120 GeV

Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

\[ \tau = 6 \text{ fm/c} \]

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

Initial jet energy: 120 GeV
Flow in QGP fluid induced by jet shower

• (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

• Evolution of medium and jet shower

\[
\tau = 6.3 \text{ fm/c} \quad e \text{ (GeV/fm}^3) \]

\[
\tau = \sqrt{(\phi^p - \phi^\text{jet})^2 + (\eta^p - \eta^\text{jet})^2}
\]

Initial jet energy: 120 GeV

Jet energy distribution

Change of jet energy

medium energy density

deposited momentum

Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

Initial jet energy: 120 GeV

Medium energy density

Jet direction

$\tau = 6.6$ fm/c

Jet energy distribution

Change of jet energy

Flow in QGP fluid induced by jet shower

- **(3+1)-D ideal hydro**
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- **Evolution of medium and jet shower**

\[
\tau = 6.9 \text{ fm}/c \quad \rho (\text{GeV}/\text{fm}^3)
\]

\[
\tau = \sqrt{(\phi_p - \phi_{\text{jet}})^2 + (\eta_p - \eta_{\text{jet}})^2}
\]

Initial jet energy: 120 GeV
Flow in QGP fluid induced by jet shower

- (3+1)-D ideal hydro
  - optical Glauber model in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV
  - EoS from lattice QCD

- Evolution of medium and jet shower

\[
\tau = 7.2 \text{ fm/c} \quad e \quad (\text{GeV/fm}^3)
\]

- Initial jet energy: 120 GeV

\[
\tau = \sqrt{(\phi_p - \phi_{jet})^2 + (\eta_p - \eta_{jet})^2}
\]

- Deposited momentum

- Change of jet energy

- Jet energy distribution

Medium contribution to jet energy loss

- Contribution of particles emitted from excited medium

\[ \Delta R: \text{jet-cone size} \]
\[ r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2} < \Delta R \]

\[ R_{\text{PbPb}} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{\text{PbPb}}/d\eta d^p_T}{d^2 N_{\text{Pp}}/d\eta d^p_T} , \]

The nuclear modification factor

\[ \text{Total Energy Loss} \]

\[ \langle \Delta E_{\text{jet}} \rangle \]

\[ E_{\text{jet init}} \text{ (GeV)} \]

\[ R_{\text{PbPb}} \]

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

Medium contribution to jet energy loss

- Contribution of particles emitted from excited medium

\[ \Delta R: \text{jet-cone size} \]
\[ r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2} < \Delta R \]

\[ R_{\text{PbPb}} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{d^2 N_{\text{PbPb}}}{d\eta_p dp_T^{\text{jet}}} \]

The nuclear modification factor

\[ \Delta R=0.3 \]

\[ \langle \Delta E_{\text{jet}} \rangle \] vs. \( E_{\text{jet} \, \text{init}} \) (GeV)

\[ R_{\text{PbPb}} \] vs. \( p_T^{\text{jet}} \) (GeV/c)
Medium contribution to jet energy loss

- Contribution of particles emitted from excited medium

\[ \Delta R: \text{jet-cone size} \]

\[ r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2} < \Delta R \]

\[ \text{counted as part of jet} \]

The nuclear modification factor

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

Medium contribution to jet energy loss

- Contribution of particles emitted from excited medium

\[ \Delta R: \text{jet-cone size} \]

\[ r = \sqrt{(\eta_p - \eta_{\text{jet}})^2 + (\phi_p - \phi_{\text{jet}})^2} < \Delta R \]

\( \Rightarrow \) counted as part of jet

\[ \Delta R = \text{counted as part of jet} \]

Jet-cone Size Dependence

(jets are generated by PYTHIA & MC Glauber)

\[ E_{\text{jet}} > 100 \text{ GeV}(\text{shower+medium}) \]

\[ E_{\text{jet}} > 100 \text{ GeV}(\text{shower}) \]

\[ E_{\text{jet}} > 50 \text{ GeV}(\text{shower+medium}) \]

\[ E_{\text{jet}} > 50 \text{ GeV}(\text{shower}) \]
Medium contribution to jet energy loss

- Contribution of particles emitted from excited medium
  (jets are generated by PYTHIA & MC Glauber)

\[ \Delta R: \text{jet-cone size} \]

\[ r = \sqrt{(\eta_p - \eta_{jet})^2 + (\phi_p - \phi_{jet})^2} < \Delta R \]

\[ \text{counted as part of jet} \]

Total Energy Loss

Jet-cone Size Dependence

Increase of jet-cone size dependence

\[ \langle \Delta E_{jet} \rangle \text{ (GeV)} \]

\[ E_{jet_{init}} \text{ (GeV)} \]
Jet shape modification

- **Jet shape function**

\[
\rho(r) = \sum_i \frac{p_T^i}{p_T^{jet}} \theta[r_i - (r - \frac{1}{2} \delta r)] \theta[(r + \frac{1}{2} \delta r) - r_i] \frac{\delta r}{\delta r}
\]

- Inclusive, \(E_{jet} \geq 100\,\text{GeV} (\Delta R = 0.3)\)

(jets are generated by PYTHIA & MC Glauber)

\[
r = \sqrt{(\phi_p - \phi_{jet})^2 + (\eta_p - \eta_{jet})^2}
\]
Jet shape modification

- Jet shape function

\[ \rho(r) = \sum_i \frac{p_T^i}{p_T^{jet}} \theta[r_i - (r - \frac{1}{2} \delta r)] \theta[(r + \frac{1}{2} \delta r) - r_i] \delta r \]

- Inclusive, \( E_{jet} \geq 100 \text{ GeV} \) (\( \Delta R = 0.3 \))

\[ r = \sqrt{(\phi_p - \phi_{jet})^2 + (\eta_p - \eta_{jet})^2} \]
Jet shape modification

- Jet shape function

\[ \rho(r) = \sum_i \frac{p_T^i}{p_T^{\text{jet}}} \theta[r_i - (r - \frac{1}{2} \delta r)] \theta[(r + \frac{1}{2} \delta r) - r_i] \]

- Inclusive, \( E_\text{jet} \geq 100 \text{ GeV} \) (\( \Delta R = 0.3 \))

![Graphs showing jet shape modification and jet shape function](image-url)

(jets are generated by PYTHIA & MC Glauber)

\[ r = \sqrt{(\phi_p - \phi_\text{jet})^2 + (\eta_p - \eta_\text{jet})^2} \]
Jet shape modification

• Jet shape function

\[
\rho(r) = \sum_i \frac{p_T^{i,jet}}{p_T^{jet}} \times \frac{\theta[r_i - (r - \frac{1}{2}\delta r)] \theta[(r + \frac{1}{2}\delta r) - r_i]}{\delta r}
\]

- Inclusive, \(E_{jet} \geq 100\) GeV \((\Delta R = 0.3)\)
Jet shape modification

- Jet shape function

\[ \rho(r) = \sum_i \frac{p_{T,i}^2}{p_{T,jet}^2} \theta[r_i - (r - \frac{1}{2} \delta r)] \theta[(r + \frac{1}{2} \delta r) - r_i] \]

- Inclusive, \( E_{jet} \geq 100 \text{ GeV} \) (\( \Delta R = 0.3 \))

Medium response to jet
Enhancement at large-\( r \)

(jets are generated by PYTHIA & MC Glauber)

\[ r = \sqrt{(\phi_p - \phi_{jet})^2 + (\eta_p - \eta_{jet})^2} \]
Summary

• **Full jet shower + hydro model**
  - Jet shower evolution: transport equations for partons in jet
  - Medium evolution: hydrodynamic equation with source term

  ![N.-B. Chang’s talk (NEXT)](constructed from jet transport equation)

• **Medium contribution to jet energy loss**
  - Increase of jet cone size dependence

• **Medium contribution to jet shape modification**
  - Further broadening of jet shape
  - Significantly modification except for very small-r
  - Medium contribution dominates large-r region
Backup
Source term

• Energy momentum conservation for QGP + jet system

\[ \partial_\mu \left[ T^{\mu\nu}_{\text{QGP}}(x) + T^{\mu\nu}_{\text{jet}}(x) \right] = 0 \]

\[ \partial_\mu T^{\mu\nu}_{\text{QGP}}(x) = J^\nu(x), \quad J^\nu(x) \equiv -\partial_\mu T^{\mu\nu}_{\text{jet}}(x) \]

\[ = - \sum_j \int \frac{d^3 k_j}{\omega_j} k_j^\nu k_j^\mu \partial_\mu f_j(k_j, x, t) \]

\[ = - \sum_j \int \frac{d^3 k_j}{\omega_j} k_j^\nu k_j^\mu \left[ \partial_\mu f_j(k_j, x, t) |_{\hat{e}, \hat{q}} \right] \]

Only coll. & broad. contribution
Energy-momentum conservation during rad. processes;

\[ \sum_j \int \frac{d^3 k_j}{\omega_j} k_j^\nu k_j^\mu \left[ \partial_\mu f_j(k_j, x, t) |_{\text{rad.}} \right] = 0 \]

Approximation: \( x_j(k, t) = x_0^{\text{jet}} + \frac{k_j^\mu}{\omega_j} \)

\[ J^\nu(x) = \sum_j \int \frac{d\omega_j dk_j^2 \omega_j}{2\pi} k_j^\nu \frac{df_j(\omega_j, k_j^2)}{dt} \bigg|_{\hat{e}, \hat{q}} \delta^{(3)}(x - x_j(k, t)) \]
Some details of model

• Jet quenching parameter $\hat{q}$

$$\hat{q}_q(x_{jet}) = \hat{q}_{q,0} \frac{T^3(x_{jet})}{T_0^3} \frac{p_{jet} \cdot u(x_{jet})}{p_{jet}^0}$$

$\hat{q}_{q,0} = 2.0 \text{ GeV}^2/\text{fm}$ (chosen to fit the experimental data of $R_{\text{PbPb}}$)

$$T_0 = T(x = 0, \tau = \tau_0) = 0.514 \text{ GeV}$$

$$\hat{q}_{g,0} = \frac{C_A}{C_F} \hat{q}_{q,0}$$

• Initial profile of medium
  - initial proper time $\tau_0 = 0.6 \text{ fm}/c$
  - optical Glauber model with $b = 0$

$$s(\tau_0, \mathbf{x}_\perp, \eta_s) = s_T(\mathbf{x}_\perp) H(\eta_s)$$

$$s_T(\mathbf{x}_\perp) = \frac{C}{\tau_0} \left[ \frac{1 - \alpha}{2} n_{\text{part}}(\mathbf{x}_\perp) + \alpha n_{\text{coll}}(\mathbf{x}_\perp) \right], H(\eta_s) = \exp \left[ -\left( \frac{\eta_s - \eta_{\text{flat}}}{2\sigma^2} \right)^2 \right]$$

$C = 19.8, \alpha = 0.14, \eta_{\text{flat}} = 3.8, \sigma = 3.2.$

• Generation of inclusive jet events
  - PYTHIA + MC Glauber Model $b = 3.5 \text{ fm}$
  - created and traveling in transverse plane $\eta_s = 0$

Jet Shape, hydro, and Jet energy deposition profile are 3D
Jet reconstruction

- Jet- $p_T$

  \[
  p_T^{\text{jet}} = p_{T,\text{shower}}^{\text{jet}} + p_{T,\text{medium}}^{\text{jet}}
  \]

  \[
  p_{T,\text{shower}}^{\text{jet}} = \sum_j p_{T,\text{shower}}^j \theta(\Delta R - r_i)
  \]

  \[
  p_{T,\text{medium}}^{\text{jet}} = \sum_i p_{T,\text{medium}}^i \theta(\Delta R - r_i) \bigg|_{w/ \text{jet}} - \sum_i p_{T,\text{medium}}^i \theta(\Delta R - r_i) \bigg|_{w/o \text{jet}}
  \]

  $j$: partons with $p_{T,\text{shower}}^j > 2$ GeV/c, $i$: hadrons with $p_{T,\text{medium}}^i > 1$ GeV/c

- $p_T$ of hadrons emitted from medium ($p_{T,\text{medium}}^i$)

  - Cooper-Frye formula

  \[
  E_i^0 \frac{dN_i}{d^3p_i} = \frac{g_i}{(2\pi)^3} \int \frac{p^\mu d\sigma_\mu}{\exp [p^\mu u^\mu(x)/T(x)] + BF 1} \rightarrow \sum_i p_{T,\text{medium}}^i = \sum_i \int d^3p_i p_{T,i} \frac{dN_i}{d^3p_i}
  \]

  \[
  u^\mu(x): \text{flow velocity, } T(x): \text{temperature, } g_i: \text{degeneracy}
  \]

  (No hadronic interaction after the hydrodynamic evolution)