Jet quenching in nuclear collisions
核碰撞中的喷注压低

Guang-You Qin
秦广友

Duke University
杜克大学
Outline

• **Introduction**

• **Probing hot QGP with jets (and photons)**
  – Jet energy loss
  – Gamma-jet correlations
  – Energy deposition by jets into medium

• **Summary**
Search for QGP

QGP: a soup of quarks and gluons
Searching for QGP = melting/heating QCD matter
Time evolution of a heavy ion collision

• Tasks:
  – Find unambiguous signatures of the QGP formation
  – Investigate the properties of hot QCD matter
  – Understand collision/expansion dynamics
  – Connect initial two colliding nuclei and final observed particles
Collectivity of hot QGP

\[
\frac{dN}{dyd^2p_Td\psi} = \frac{dN}{dy(2\pi p_T)dp_T} \left[1 + 2v_2 \cos(2\psi) + \ldots\right]
\]

- The strong collectivity is well described by relativistic hydrodynamics
- The collective flow is anisotropic in non-central collisions
- The initial spatial anisotropy translates into final momentum anisotropy of emitted particles
Relativistic hydrodynamics

- Based on conservation law

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

\[ T^{\mu\nu} = (e + p + \Pi)u^\mu u^\nu - (p + \Pi)g^{\mu\nu} + \pi^{\mu\nu} \]

- Also evolution equations for bulk and shear pressure tensor

- Describe the transport of macroscopic degrees of freedom
- Assume local thermal equilibrium

- Inputs:
  - equation of state: \( e = e(p) \)
  - initial energy momentum tensor (energy/entropy density, flow \( u \), transport coefficients: \( \zeta, \eta \) ...)

...
Hydro results

Hydrodynamic calculations with zero viscosity reasonably describe the bulk matter
Equilibration time $t_0=0.1-1$ fm/c and $\varepsilon_0=20-60$ GeV/fm$^3$

$$\frac{dN}{dyd^2p_Td\psi} = \frac{dN}{dy(2\pi p_T)dp_T} \left[1 + 2v_2 \cos(2\psi) + \ldots \right]$$
"Perfect" fluid at RHIC

- On 04/18/2005, BNL announced a press that RHIC had created a new state of hot and dense matter which behaves like a nearly perfect liquid.

- How perfect is this fluid? How small is the viscosity?
Extracting $\eta/s$

Shear viscosity tends to suppress the buildup of the flow that can be achieved in ideal hydro.

Current efforts based on hydro and other transport approaches give:

$\eta/s < 0.5$

Schenke, Jeon, Gale, 2010;
Romatschke, Romatschke, 2007;
Song, Heinz, 2008;
Dusling, Teaney, 2008 ...

Xu, Greiner, Stocker, PRL 2008;
Drescher, Dumitru, Gombeaud, Ollitrault, PRC, 2007...
Probing hot QCD matter with jets

• **Medium can modify jet propagation**
  • Jets lose energy by induced radiation and elastic collisions

• **Jet propagation can modify medium**
  • Jets dump energy into medium
  • Deposited energy diffuses down to medium scale
  • Medium responds to the excess energy
Jet quenching at RHIC

Jet quenching = partons energy loss

Hadrons are suppressed in Au+Au,
No suppression for photons
(colorless probe)
No suppression for d+Au (cold nuclear matter)
Jet energy loss schemes in the market

• **Modeling of medium**
  – A collection of static scattering centers (BDMPS, Zakharov, GLV, ASW)
  – Thermally equilibrated, perturbative medium (AMY)
  – General nuclear medium with a short correlation length (Higher Twist)

• **Resummation schemes**
  – Sum over all possible soft interactions (BDMPS, AMY)
  – Path integral representation of hard parton propagation (Zakharov, ASW)
  – Opacity expansion (GLV)

• **Evolution scheme (multiple emissions)**
  – Poisson ansatz (BDMPS, GLV, ASW)
  – Rate equations (AMY)
  – Modified DGLAP equations (Higher Twist)
General idea of Eloss calculation (AMY)

- **Hadron production factorized into three pieces:**
  \[
  \sigma_{\text{hadron}} \sim \sigma_{\text{parton}} \otimes \text{parton evolution in medium} \otimes D_{\text{vacuum}}
  \]

- **Medium modified FF defined as**
  \[
  \tilde{D}_{h/j}(z) = \sum_{j'} \int dp_{j'} \frac{z'}{z} P(p_{j'} | p_j) D_{h/j'}(z')
  \]

- **Evolve jets in a set of coupled evolution equations**
  \[
  \frac{dP_j(E, t)}{dt} = \sum_{ab} \int d\omega \left[ P_a(E + \omega, t) \frac{d\Gamma_{a\rightarrow j}(E + \omega, \omega)}{d\omega dt} - P_j(E, t) \frac{d\Gamma_{j\rightarrow b}(E, \omega)}{d\omega dt} \right]
  \]

- **Partonic rates (dependent on medium properties) calculated from finite temperature field theory**

- **Medium information T(x), u(x) taken from hydrodynamic simulation**
Induced gluon emission

AMY formalism: based on finite temperature field theory, complete leading order result!

Collinear gluon emission induced by multiple soft scatterings

The induced emissions of photons and gluons are treated together consistently

Including elastic energy loss (GYQ, Ruppert, Gale, Jeon, Moore and Mustafa, PRL, 2008)

Arnold, Moore, Yaffe, JHEP, 2001; 2001; 2002
Evolution of parton distributions

\[
\frac{dP_q(p)}{dt} = \int_k P_q(p+k) \frac{d\Gamma_{qq}^q(p+k,k)}{dkdt} - P_q(p) \frac{d\Gamma_{qq}^q(p,k)}{dkdt} \\
+ 2P_g(p+k) \frac{d\Gamma_{qg}^g(p+k,k)}{dkdt}
\]

\[
\frac{dP_g(p)}{dt} = \int_k P_q(p+k) \frac{d\Gamma_{qq}^q(p+k,p)}{dkdt} + P_g(p+k) \frac{d\Gamma_{gg}^g(p+k,k)}{dkdt} \\
- P_g(p) \left( \frac{d\Gamma_{qq}^g(p,k)}{dkdt} + \frac{d\Gamma_{gg}^g(p,k)}{dkdt} \Theta(2k-p) \right)
\]

Evolve entire parton distributions
Include complete parton split (fusion) processes
Keep track of produced daughters
Elastic E-loss included as well

GYQ, Ruppert, Gale, Jeon, Moore and Mustafa, PRL, 2008
GYQ, Ruppert, Gale, Jeon, Moore, PRC, 2009
Schenke, Gale, GYQ, PRC, 2009
GYQ, Ruppert, Turbide, Gale, Nonaka, Bass, PRC 2007
Turbide, Gale, Jeon, and Moore, PRC, 2005.
Jeon, Moore, PRC, 2005
Jet energy loss

Different evolution patterns from radiative and collisional energy loss
Average E-loss dominated by radiations
Contribution from elastic collisions to $R_{AA}$ not negligible

GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL, 2008.
Limitations of $R_{AA}$

Single particle $R_{AA}$ doesn’t work: flat!!!

Models with various underlying physics can describe the flat data

Average over different production points and propagation directions (path lengths)

Convolution of parton production and parton fragmentation (hadron with certain $p_T$ involves partons with various $p_T$)

Need more differential observables

$R_{AA}$ vs reaction plane: get length dependence

Ideal to fix parton $p_T$: gamma-get correlations, jet reconstruction

Bass, Gale, Majumder, Nonaka, GYQ, Renk, Ruppert, PRC, 2009
$R_{AA}$ vs reaction plane

**Diagram:**
- The diagram illustrates the reaction plane for charged pion production in high-energy collisions.
- The reaction plane is defined by the $x$- and $y$-axes, with the $z$-axis perpendicular to the plane.
- The reaction plane is divided into sectors based on the azimuthal angle $\Delta \phi$.
- The plots show the $R_{AA}$ (rapidity and azimuthal angle) as a function of $p_T$ (transverse momentum) for different $\Delta \phi$ ranges.

**Plots:**
- Each plot represents a different $\Delta \phi$ range (e.g., $0^\circ < \Delta \phi < 15^\circ$, $75^\circ < \Delta \phi < 90^\circ$).
- The $R_{AA}$ values are shown for the $\pi^0$ and $\pi^+$/\$\pi^-$ ratios.
- The data points are compared to theoretical predictions (e.g., AMY, ASW models).

**Legend:**
- PHENIX Preliminary
- $0^\circ < \Delta \phi < 15^\circ$
- $75^\circ < \Delta \phi < 90^\circ$
- HT in
- HT out
- AMY in
- AMY out
- ASW in
- ASW out
Gamma-jet tomography

“Golden” channels dominate hard photon production: $q + g \rightarrow q + \gamma$, $g + q \bar{q} \rightarrow g + \gamma$

Parton $p_T$ determined by the trigger photon
Medium-modified FF directly measured
Potential to distinguish different E-loss models

Wang, Zhang, Sarcevic, RRL, 2006
Renk, PRC, 2006
Majuder, Van Leeuwen, arXiv:1002.2206
Photon can be produced from jets

Except “golden” channels, photons can be produced during and after the passage of jets in the medium:
- jet-fragmentation photons
- jet-photon conversion
- induced photon radiation

Jet-initiated photon sources will change the shape of gamma-tagged jets (see later)

GYQ, Ruppert, Gale, Jeon, Moore, PRC, 2009
Compute various photons

- **Hard direct photons from early collisions**: pQCD calculation with proper initial isospin and shadowing effect

- **Fragmentation photons** from surviving jets after the passage of medium: Jet E-loss model + photon FF

- **Jet-medium photons**: produced from jets simultaneously with jet evolution

\[
\frac{dP_{\gamma}^{\text{jet-plasma}}(E, t)}{dt} = \int d\omega P_{q\bar{q}}(E+\omega, t) \left( \frac{d\Gamma_{q\rightarrow\gamma}^{\text{brem}}(E+\omega, \omega)}{d\omega dt} + \frac{d\Gamma_{q\rightarrow\gamma}^{\text{conv}}(E+\omega, \omega)}{d\omega dt} \right).
\]

- Photon bremsstrahlung rate and jet-photon conversion rate are obtained from thermal field theory
Photons @ RHIC

High $p_T$ dominated by initial hard direct photons

Important contribution from jet-medium photons at intermediate $p_T$

Thermal photons not included, dominated at low $p_T$

Negative $v_2$ from jet-medium photons are compensated by other sources

Centrality cut and isolation of frag. photons is helpful to see the signal of negative $v_2$

GYQ, Ruppert, Gale, Jeon, Moore, PRC, 2009
Tagging jets with different photons

A large fraction of hadrons at high $p_T(z_T)$ come from jets tagged by jet-medium photons and fragmentation photons.

Different photon-tagged jets have different shapes.

The associated jets at production time tend to have more $p_T$ than the triggered photon.

Note NLO for initial hard photon production would change the kinematics.

**GYQ, Ruppert, Gale, Jeon, Moore, EPJC, 2008**

**GYQ, Ruppert, Gale, Jeon, Moore, PRC, 2009**
Gamma-h status @ RHIC

\[ I_{AA} = \frac{P_{AA}(p_T^h | p_T^{\gamma})}{P_{pp}(p_T^h | p_T^{\gamma})} = \frac{D_{AA}(z_T, p_T^{\gamma})}{D_{pp}(z_T, p_T^{\gamma})} \]

Direct $\gamma$ triggers

8 < $p_T^{\gamma}$ < 16 GeV/c

\[ z_T = \frac{p_T^{assoc}}{p_T^{trig}} \]
Medium response to jet transport

• A Mach cone is formed when an object moves faster than the speed of sound in the medium.

• Is a Mach cone created when a parton propagates through the quark gluon plasma?

Jets dump energy into medium
Deposited energy diffuses to medium
Medium responds to the excess energy.
Energy deposition by jet

Jet loses/deposits energy and momentum through elastic collisions/absorption
This will lead to ~constant energy deposition rate
Energy deposition by jet

Jet loses/deposits energy and momentum through elastic collisions/absorption
This will lead to ~constant energy deposition rate

Jets lose energy also by radiations
Energy deposition by jet

Jet loses/deposits energy and momentum through elastic collisions/absorption. This will lead to ~constant energy deposition rate.

Jets lose energy also by radiations. The radiations serve as additional sources for energy deposition. This will lead to non-constant energy deposition rate.
Energy deposition by jet

Jet loses/deposits energy and momentum through elastic collisions/absorption. This will lead to a constant energy deposition rate.

Jets lose energy also by radiations. The radiations serve as additional sources for energy deposition, leading to a non-constant energy deposition rate.

Use higher twist formalism.
Jet evolution in vacuum

\[
\frac{\partial D_{i\rightarrow h}(z, Q^2)}{\partial \ln Q^2} = \sum_j \frac{\alpha_s}{2\pi} \int \frac{dy}{y} P_{i\rightarrow j}(y) D_{j\rightarrow h}(z/y, Q^2)
\]
Look backwards

\[ D(z, \mu^2) = \text{Contains all emissions up to scale } \mu \]
Look backwards

\[ D(z, \mu^2) = \]

Contains all emissions up to scale \( \mu \)

\[ D(z, \mu^2 + \delta \mu^2) = \]

\[ + \]
Look backwards

\[ D(z, \mu^2) = \]

Contains all emissions up to scale \( \mu \)

\[ D(z, \mu^2 + \delta \mu^2) = \]

\[ D(z, \mu^2 + \delta \mu^2 + \delta \mu^2) = \]

\[ + \]

\[ + \]
Look backwards

\[ D(z, \mu^2) = \]

\[ D(z, \mu^2 + \delta \mu^2) = \]

\[ D(z, \mu^2 + \delta \mu^2 + \delta \mu^2) = \]

Increasing the scale = rebuilding the shower

Evolution governed by DGLAP equations

\[ \frac{\partial D_{i \rightarrow h}(z, Q^2)}{\partial \ln Q^2} = \sum_j \frac{\alpha_s}{2\pi} \int \frac{dy}{y} P_{i \rightarrow j}(y) D_{j \rightarrow h}(z/y, Q^2) \]
Jet evolution in medium

Jet shower is modified by multiple scatterings

\[ D(z, \mu^2 + \delta \mu^2) = \]

\[ + \]

\[ + \]

medium-induced contribution
Medium-modified FF

For soft kicks, $k_T \ll l_T$, medium-dependent correction to FF

$$\Delta \tilde{D}_{i\rightarrow h}(z, Q^2, q^-)|_{\tilde{\zeta}_i}^{\tilde{\zeta}_f} = \sum_j \int \frac{d\ell_{1j}^2}{l_{1j}^4} \frac{\alpha_s}{2\pi} \int \frac{dy}{y} P_{i\rightarrow j}(y) \int_{\tilde{\zeta}_i}^{\tilde{\zeta}_f} d\zeta \frac{\tilde{q}(\zeta)}{\pi} \left[ 2 - 2\cos \left( \frac{l_{1j}^2 (\zeta - \zeta_i)}{2q^-y(1-y)} \right) \right] \tilde{D}_{j\rightarrow h}(z/y, l_{1j}^2, q^-y)|_{\tilde{\zeta}}^{\tilde{\zeta}_f}$$

$$\tilde{q} = d(\Delta p_T)^2 / dt$$

For $l_T$ ordered emissions, DGLAP for MMFF

$$\frac{\partial \tilde{D}_{i\rightarrow h}(z, Q^2, q^-)|_{\tilde{\zeta}_i}^{\tilde{\zeta}_f}}{\partial \ln Q^2} = \sum_j \frac{\alpha_s}{2\pi} \int \frac{dy}{y} \int_{\tilde{\zeta}_i}^{\tilde{\zeta}_f} d\zeta \tilde{P}_{i\rightarrow j}(y, \zeta, Q^2, q^-) \tilde{D}_{j\rightarrow h}(z/y, Q^2, q^-)|_{\tilde{\zeta}}^{\tilde{\zeta}_f} + \text{vacuum part}$$

$$\tilde{P}_{i\rightarrow j} = P_{i\rightarrow j}(y) \frac{\tilde{q}(\zeta)}{\pi Q^2} \left[ 2 - 2\cos \left( \frac{\zeta - \zeta_i}{\tau_f} \right) \right]$$

$$\tau_f = \frac{2q^-y(1-y)}{l_{1j}^2}$$

Jet energy loss in HT

Specify the transport coefficients as

$$\hat{q} \propto T^3$$

$$\frac{d(\Delta p^\perp)^2}{dt} \simeq 2 \frac{d(\Delta p_z)^2}{dt} \simeq \frac{4T}{|v|} \frac{dp_z}{dt}$$

Partons with formation lengths $\tau_f = E/Q^2$ larger than the path length $L$ will not be modified by the medium $\mu_0^2 = \max(E/L, 1\text{GeV}^2)$

Elastic loss included with both longitudinal drag and diffusion

$$D'(z) = \int d\Delta z P(\Delta z) D(z/(1-\Delta z))/(1-\Delta z)$$

$$\hat{q}_0 \approx 1.3 \text{ GeV}^2/\text{fm} \text{ at } T = 400 \text{ MeV} \tau_0 = 0.6 \text{ fm}$$

with Majumder
Similar to evolution of FF

Suppose at some low scale $\mu$, we know the energy deposit rate $dE/dL$

$$\Delta E(\mu^2)|_{\zeta_i}^{\zeta_f} = \int_{\zeta_i}^{\zeta_f} d\zeta \frac{dE}{dL}(\zeta) = \zeta_i \quad \zeta_f$$

This contains the contribution to energy deposition from all emissions up to $\mu$
Similar to evolution of FF

Suppose at some low scale $\mu$, we know the energy deposit rate $dE/dL$

$$\Delta E(\mu^2)|_{\zeta_i}^{\zeta_f} = \int_{\zeta_i}^{\zeta_f} d\zeta \frac{dE}{dL}(\zeta) = \zeta_i - \zeta_f$$

This contains the contribution to energy deposition from all emissions up to $\mu$

Now increase the virtuality, jet tends to drop virtuality by radiation
Similar to evolution of FF

Suppose at some low scale \( \mu \), we know the energy deposit rate \( \frac{dE}{dL} \)

\[
\Delta E(\mu^2)|_{\zeta_i}^{\zeta_f} = \int_{\zeta_i}^{\zeta_f} \frac{dE}{dL}(\zeta) = \zeta_i \quad \zeta_f
\]

This contains the contribution to energy deposition from all emissions up to \( \mu \)

Now increase the virtuality, jet tends to drop virtuality by radiation

One may write down similar evolution equation for energy deposition

\[
\frac{d\Delta E_q(E, Q^2)}{d \ln Q^2}|_{\zeta_i}^{\zeta_f} = \frac{\alpha_s}{2\pi} \int dy \int_{\zeta_i}^{\zeta_f} d\zeta \tilde{P}_{q\rightarrow qg}(y, \zeta, Q^2, E)
\]

\[
\left[ \Delta E_q(E, Q^2)_{\zeta_i}^{\zeta_f} + \Delta E_q(yE, Q^2)_{\zeta}^{\zeta_f} + \Delta E_g((1-y)E, Q^2)_{\zeta_f}^{\zeta_f} \right]
\]

Similar evolution equations for momentum deposition!
Energy and transverse momentum deposition are enhanced by radiative shower.

GYO, Majumder, Song, Heinz, PRL (2009)

Use HTL result as input at scale $\mu_0=4T$

$$
\frac{d\Delta E(\mu_0, E)}{d\zeta} = \frac{C_R \alpha_s(\mu_0^2) m_D^2}{4} \ln \left[ \frac{4ET}{m_D^2} \right]
$$

Energy/momentum deposition
What happens to the excess energy?

- Assume the deposited energy gets thermalized after a relaxation time $\tau_R = 1/m_D$

- Treat the energy/momentum deposition as a source term (only energy deposition included here)

\[
J^\mu \equiv \left[ \frac{d \Delta E(\mu, E)}{d \zeta}, 0, 0, \frac{dp_z(\mu, E)}{d \zeta} \right] \delta^2(\vec{r}_\perp) \delta(t-z).
\]

- Assume energy deposited is a small perturbation, we solve linear hydro equation

\[
T^{\mu\nu} \simeq T_0^{\mu\nu} + \delta T^{\mu\nu}; \quad \partial_\mu T_0^{\mu\nu} = 0, \quad \partial_\mu \delta T^{\mu\nu} = J^\nu.
\]

- Decompose the small excess energy-momentum tensor as

\[
\begin{align*}
\delta T^{00} & \equiv \delta \epsilon, \\
\delta T^{0i} & \equiv \delta g^i, \\
\delta T^{ij} & = \delta_{ij} c_s^2 \delta \epsilon - \frac{n}{s T} \left( \partial^i g^j + \partial^j g^i - \frac{2}{3} \delta_{ij} \nabla \cdot \vec{g} \right).
\end{align*}
\]
The response of medium

Multiple emissions increase the energy deposition, producing an enhanced Mach cone

Note different vertical scales

**GYQ, Majumder, Song, Heinz, PRL (2009)**
Summary

• Jet quenching has provided valuable information about hot QGP

• Very rich (and complicated) physics underlying jet-medium interaction

• Both radiations and collisions are important for jet-medium interaction (energy loss and energy deposition)

• Photons (and jet-photon correlations) can provide additional information about jet-quenching

• Simulate jet propagation, photon production, medium evolution together

• LHC will provide new opportunities (hotter QGP, much higher energy jets and much brighter photons)