Z^0 Tagged Jets as a Probe of the QGP

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Presentation of work done at
Los Alamos National Lab
Introduction
Jet Quenching at RHIC – experimentally well established

\[
R_{AA}(p_T, \eta) = \frac{1}{< N_{coll}>} \cdot \frac{d^2 \sigma^{AA}}{d\eta dp_T} / \frac{d^2 \sigma^{NN}}{d\eta dp_T}
\]

PHENIX Au+Au (central collisions):
- Direct $\gamma$
- $\pi^0$
- $\eta$
- GLV parton energy loss ($dN/dy = 1100$)
Jet quenching as a probe of QGP

- Large leading particle suppression strong evidence for formation of QGP in HIC
- Parton energy loss sensitive probe of medium density, Debye scale, strong coupling, transport coefficients
Limitations of leading particle suppression

- $R_{AA}$ for single particle or $I_{AA}$ for two particle correlations only measure the leading fragments of a jet.
- Jets: a spray of final-state particles moving roughly in the same direction.
- LP $R_{AA}$ can be fit by formalisms with very different assumptions.

\[ R_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} \]
The future of jet quenching physics-
Jet shapes and jet cross sections

Explore the fraction of energy lost and variation of $R_{AA}$ with changing cone radius/$p_{T\text{min}}$

\[
\Psi_{\text{int}}(r; R) = \frac{\sum_i (E_T)_i \Theta(r - (R_{\text{jet}})_i)}{\sum_i (E_T)_i \Theta(R - (R_{\text{jet}})_i)},
\]

\[
\psi(r; R) = \frac{d\Psi_{\text{int}}(r; R)}{dr}.
\]


Bryon Neufeld at WWND, January 2010
A theory of jet shapes and cross sections: from hadrons to nuclei, I Vitev, S Wicks, BWZ, JHEP 0811,093 (2008)

Investigated for inclusive jets using GLV energy loss formalism

\[
\begin{align*}
k^+ \frac{dN_g}{dk^+ d^2k_\perp} &= \sum_{n=1}^{\infty} k^+ \frac{dN^n_g}{dk^+ d^2k_\perp} = \sum_{n=1}^{\infty} \frac{C_R \alpha_s}{\pi^2} \left[ \prod_{i=1}^{n} \int_{t_i}^{t_i-\Delta t_i} \frac{d \Delta z_i}{\lambda_g(z_i)} \right] \int d^2 q_i \left( \frac{1}{\sigma_{el}} \frac{d\sigma_{el}}{d^2 q_i} - \delta^2(q_i) \right) \\
&\times \left[ -2C_{(1...n)} \cdot \sum_{m=1}^{n} B_{(m+1...n)(m...n)} \left( \cos \left( \sum_{k=2}^{m} \omega_{(k...n)} \Delta z_k \right) - \cos \left( \sum_{k=1}^{m} \omega_{(k...n)} \Delta z_k \right) \right) \right]
\end{align*}
\]

Number of scatterings  Momentum transfers

Color current propagators  Coherence phases (LPM effect)
Initial Geometry

$S_{NN}^{1/2} = 5.5 \text{ TeV, } \sigma_{in} = 65 \text{ mb}$

Optical Glauber

QGP density (3D) $\sim$ participant density (2D)

Pb+Pb at $b=3 \text{ fm}$

Binary collision density (2D) -- corresponds to jet production

Note the difference in the distributions
Energy loss distribution

\[ \frac{\Delta E^{in}}{E}(R_{\text{max}}, \omega_{\text{min}}) = \frac{1}{E} \int_{\omega_{\text{min}}}^{E} d\omega \int_{0}^{R_{\text{max}}} dr \frac{dIg}{d\omega dr}(\omega, r) \]

- Energy ratio goes down with larger \( b \).
- Energy ratio becomes smaller with smaller \( R \) and larger \( \omega_{\text{min}} \).
Inclusive Jet cross section @HIC and $R_{AA}$

$$\frac{\sigma^{AA}(R, \omega^{\text{min}})}{d^2 E_T dy} = \int_{\epsilon=0}^{1} d\epsilon \sum_{q,g} P_{q,g}(\epsilon) \frac{1}{(1 - (1 - f_{q,g}) \cdot \epsilon)^2} \frac{\sigma^{NN}(R, \omega^{\text{min}})}{d^2 E'_T dy}$$

$$E'_T = E_T / (1 - (1 - f_{q,g}) \cdot \epsilon)$$

**Define nuclear modification factor for jet cross section:**

$$R_{AA}^{\text{jet}}(E_T; R^{\text{max}}, \omega^{\text{min}}) = \frac{d\sigma^{AA}(E_T; R^{\text{max}}, \omega^{\text{min}})}{dy d^2 E_T} / \langle N_{\text{bin}} \rangle \frac{d\sigma^{PP}(E_T; R^{\text{max}}, \omega^{\text{min}})}{dy d^2 E_T}$$

**Centrality dependence of $R_{AA}$ for jet cross section is similar to that for single hadron production**

$$f = \frac{\Delta E_{\text{rad}} \{ (0, R); (\omega^{\text{min}}, E) \}}{\Delta E_{\text{rad}} \{ (0, R^{\infty}); (0, E) \}}$$
$R_{AA}$ vs $R^{\text{max}}$ and $\omega^{\text{min}}$

- $R_{AA}$ for jet cross section evolves continuously by varying cone size and acceptance cut.
- Contrast: single result for leading particle
- Limits: $R_{AA}$ approaches to single hadron suppression with $R^{\text{max}}$ and large $\omega^{\text{min}}$
Tagging with $Z^0$ boson
Tagged Jets

Consider both $Z^0$+jet and $\gamma^*$+jet (small correction)

$Z^0$+jet has small yield, but is excellent handle for jet energy loss

\[ R_q^2 + L_q^2 = \tau_q^2 - 4 e_q \tau_q \sin^2 \theta_w + 8 e_q^2 \sin^3 \theta_w. \]
From $Z^0$ to dileptons

- Experimentally, dileptons are observed. We perform the decay by a Lorentz boost weighted with branching ratio.
Comparison to Data

- $Z^0$+jet measurements recently became available

As expected within 30% - 50% of the data. Shape is reasonably well described, NLO in progress.
At LO, quenched cross section takes simple form, probes $P(\varepsilon)$, $f$

\[
\frac{d\sigma}{dy_3 dy_4 dp_T^3 dp_T^4} = P(1 - \frac{p_T^4}{p_T^1}) q,g \frac{|M|^2 \delta(x_1 - \bar{x}_1)\delta(x_2 - \bar{x}_2)}{(2\pi)^2 4 x_1 x_2 S^2 (1 - f)}
\]

\[
\varepsilon = \sum_{i=1}^n \frac{\omega_i}{E}, \quad P(\varepsilon) = \sum_0^\infty P_n(\varepsilon) \quad P_0(\varepsilon) = e^{-\langle N_g \rangle} \delta(\varepsilon)
\]

\[
P_1(\varepsilon) = \frac{dN}{d\varepsilon} (\varepsilon), \quad P_n(\varepsilon) = \frac{1}{n} \int_0^\varepsilon d\varepsilon' P_{n-1}(\varepsilon - \varepsilon') \frac{dN}{d\varepsilon} (\varepsilon')
\]

\[
\int_0^1 d\varepsilon' P(\varepsilon') = 1, \quad \int_0^1 d\varepsilon' \varepsilon' P(\varepsilon') = \frac{\langle \Delta E \rangle}{E}
\]

Example of probability density

GLV, BDMPS (ASW)
Obtaining the number of radiated gluons

\[ \langle N^g \rangle = -\ln (R_{AA}) \]

Constrain \( p_{T3} = p_{T4} \)

\( R_{AA} (p_{T3} = p_{T4}) \)

- Red: Quark Jets (all R)
- Blue: Gluon Jets (all R)

\( s^{1/2} = 5.5 \text{ TeV}, b=3 \)

Pb+Pb collisions at the LHC

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The form of the quenched cross section

Consider $p_{T,\text{jet}} < p_{T,\text{Z}}$

\[
\frac{d\sigma^{\text{Quench}}}{dy_Z dy_{\text{jet}} dp_{T,\text{Z}} dp_{T,\text{jet}}} = \sum_{q,g} \frac{d\sigma^{pp}}{dy_Z dy_{\text{jet}} dp_{T,\text{Z}}} \times \frac{1}{p_{T,\text{Z}}(1 - f_{q,g})} \times P\left(\frac{1 - p_{T,\text{jet}} / p_{Z,\text{jet}}}{1 - f_{q,g}}\right)
\]

$\eta_{\text{jet}} \leq 1$

$\eta_{e^+,e^-} \leq 1$

$\sigma/dp_{T,\text{Z}} dp_{T,\text{jet}}$ [pb/GeV$^2$]

$p_{T,\text{Z}} = 100$ GeV

$Z^0$ to $e^+$+$e^-$ mode

Neufeld, IV, Zhang (2010)
Jet quenching is well established experimentally, however, leading particle suppression by itself provides incomplete information.

Jet shapes and jet cross sections may be able to distinguish between energy loss formalisms, determine fundamental properties of QGP.

The theory of jet shapes and jet cross sections in nuclear collisions has been developed by VWZ, and applied to inclusive jets at LHC.

Work now shifting to tagged jets, here presented preliminary results on $Z^0$ tagged jets at LHC energies.
Backup
Z^0 Tagged Jets at LHC
with GLV Quenching

\[ I_{AA} \]

- \( R = 0.2 \)
- \( R = 0.4 \)
- \( R = 0.7 \)
- \( R = 1.0 \)

Pb+Pb 5500 GeV
\( b = 3 \) fm

Preliminary Results

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What to use for the source term?

A common choice:

$$J^\nu(x) = \frac{dE}{dt} (1, \vec{u}) \delta(\vec{x} - \vec{u}t)$$

- Conserves energy and momentum globally (simply integrate the equation of motion over all space)
- Neglects local excitations, terms which integrate to zero globally
The linearized hydro equations couple to the source term, in turn yielding the particle emission spectrum

\[ \delta \varepsilon(\vec{k}, \omega) = \frac{i k J_L(\vec{k}, \omega) + J^0(\vec{k}, \omega)(i\omega - \Gamma_s k^2)}{\omega^2 - c_s^2 k^2 + i\Gamma_s \omega k^2} \]

\[ \bar{g}_L(\vec{k}, \omega) = \frac{i \omega \hat{k} J_L(\vec{k}, \omega) + i c_s^2 \vec{k} J^0(\vec{k}, \omega)}{\omega^2 - c_s^2 k^2 + i\Gamma_s \omega k^2} \]

\[ \bar{g}_T(\vec{k}, \omega) = \frac{i \bar{J}_T(\vec{k}, \omega)}{\omega + \frac{3}{4} i\Gamma_s k^2} \]

\[ \frac{dN}{dy \, d\phi}(y = 0) = \int_{p_T^i}^{p_T^f} dP_T \, P_T \int d\Sigma P^\mu (f(p) - f_{eq}(p)) \]