Completing mechanisms behind single inclusive jet suppression

Yayun He et al, arXiv:1809.02525
Parton energy loss and leading hadrons

\[
\frac{dE_{el}}{dx} = \int \frac{d^3k}{(2\pi)^3} dq_{\perp}^2 f(k) \frac{q_{\perp}^2}{2k} d\sigma d^2 q_{\perp} \approx C \frac{3\pi}{2} \alpha_s^2 T^2 \ln \frac{s^*}{4\mu_D^2}
\]

\[
\frac{dE_{rad}}{dx} \approx \frac{2C_A \alpha_s}{\pi} \hat{q}(x) \int dz \frac{d\ell_{\perp}^2}{\ell_{\perp}^4} z P(z) \sin^2 \frac{\ell_{\perp}^2 (x - x_0)}{4z(1 - z)E}
\]

(High-twist approach)

Parton energy loss leads to suppression of leading hadrons

Energy loss distribution \( \tilde{P}_{a \rightarrow ag}(z) \)

Modified frag function & hadron spectra:

\[
\tilde{D}_{c/h}(z_h) \approx \tilde{P}_{a \rightarrow ag}(z) \otimes D_{a/h}(z_h)
\]

\[
d\sigma_h = \sum_{a, b, c} f_a \otimes f_b \otimes d\sigma_{ab \rightarrow c+X} \otimes \tilde{D}_{c/h}
\]
q hat from $R_{AA}$ for leading hadrons

\[ \hat{q}_0 = 0.8, 1.0, 1.2, 1.4, 1.7 \text{ GeV}^2/fm \]

\[ \hat{q}/T^3(\text{DIS}) \]

\[ \hat{T} = 0, 0.1, 0.2, 0.3, 0.4, 0.5 \text{ GeV} \]

JET Collaboration: PRC90 (2014) 1, 014
Suppression of single jets at LHC

Surprise: jet energy loss at ~ 1 TeV; intriguing phenomena:

- $s^{1/2}$ dependence
- $p_T$ dependence
- $R$ dependence
- Centrality dep.
- $v_2^{jet}$
Jet energy and background subtraction

Jet energy as defined in the jet reconstruction algorithm
Uncorrelated background should be subtracted
Jet-induced medium response is correlated with jet: not background
Some of the energy lost by leading partons remain inside jet-cone
Jet energy loss: elastic & radiative

Jet energy loss due to out-of-cone jet-medium interaction

Elastic and radiative processes

XNW, Wei & Zhang, PRC96(2017)034903

(energy loss for a quark jet produced at r=0 in 0-10% Pb+Pb @2.76 TeV)
LBT: Linear Boltzmann Transport

\[ p_1 \cdot \partial f_1 = - \int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12 \rightarrow 34}|^2 (2\pi)^4 \delta^4 (\sum p_i) + \text{inelastic} \]

Induced radiation

\[ \frac{dN_g}{dz d^2 k_{\perp} dt} \approx \frac{2CA\alpha_s}{\pi k_{\perp}^4} P(z) \hat{q}(\hat{p} \cdot u) \sin^2 \frac{k_{\perp}^2 (t - t_0)}{4z(1 - z)E} \]

- pQCD elastic and radiative processes (high-twist)
- Transport of medium recoil partons (and back-reaction)
- CLVisc 3+1D hydro bulk evolution

Li, Liu, Ma, XNW and Zhu, PRL 106 (2010) 012301
LBT: Jet-induced medium response

Energy distr. of medium response

He, Luo, XNW & Zhu, PRC91 (2015) 054908
Centrality dependence

Pythia8: initial jet production (agrees with pp data)
CLVisc hydro with AMPT e-by-e initial conditions (fitted to bulk hadron spectra)
FASTJET: anti-kt (modified to take into account of negative particles)
Medium response reduces jet energy loss

Recoil partons within the jet cone reduce the net jet energy loss—change pt dependence

Diffusion wake (backreaction) reduces the thermal background, if taken into account, increase the net jet Energy loss with given cone-size

Depend on jet cone-size R
Sensitive to radial flow

He, Cao, Chen, Luo, Pang & XNW 1809.02525
Energy and $p_T$ dependence

Jet energy loss increases ($2.76$ TeV $\rightarrow$ $5.02$ TeV)
Initial spectra becomes flatter
$p_T$ dependence of jet energy loss different due to medium recoil
Energy and pT dependence

Weak pT dependence: initial jet spectra and pT dependence of energy loss ΔE
Weak energy dependence: increase of jet energy loss and the slope of initial spectra

He, Cao, Chen, Luo, Pang & XNW 1809.02525
Jet cone-size dependence

Medium response increases R-dependence of jet energy loss

Radial flow transport energy to larger angle $\rightarrow$ increases R-dependence
Flavor and rapidity dependence

- Medium response effect is stronger for gluon jets
- Gluon/quark jet energy loss ratio is 1.2 -- 1.4
- Rapidity of initial
Predictions at RHIC

anti-$k_t$ R = 0.3

0.2 < $|y|$ < 0.8

$\sqrt{s} = 200$ GeV

R = 0.4

LBT $\alpha_s = 0.15$

0.2 < $|y|$ < 0.8

$\Delta p_T$ (GeV)

$R_{AA}$

$p_T$ (GeV)
Single jet anisotropy

\[ \langle v_{n} \cos[n(\phi_{\text{jet}} - \Psi_{n})] \rangle = \frac{v_{\text{jet}}^{n}}{\sqrt{\langle v_{n}^{2} \rangle}} \]

\[ v_{\text{jet}}^{n} = \frac{\langle v_{n} \cos[n(\phi_{\text{jet}} - \Psi_{n})] \rangle}{\sqrt{\langle v_{n}^{2} \rangle}} \]
Correlation btw jet and bulk anisotropy

$$\nu_{\eta}^{jet} = \langle \cos[n(\phi_{\eta}^{jet} - \Psi_{\eta})] \rangle$$
Jet energy loss distributions

Flavor averaged jet energy loss distribution

\[ W_{AA}(\Delta p_T / \langle \Delta p_T \rangle, R) \]

\[ W_{AA}(x) = \frac{\alpha^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\alpha x} \]

\[ \equiv \int \prod_{i=1}^{\alpha} dx_i e^{-\sum_{i}^{\alpha} x_i \delta(x - \sum_{i=1}^{\alpha} x_i)} \]

He, Cao, Chen, Luo, Pang & XNW 1809.02525
Bayesian analysis of experimental data

\[ \frac{d\sigma_{\text{jet}}^{\text{AA}}}{dp_T dy} = \int d\Delta p_T W_{\text{AA}}(\Delta p_T, p_T + \Delta p_T, R) \frac{d\sigma_{\text{pp}}}{dp_T dy} \bigg|_{p_T = p_T + \Delta p_T} \]

\[ W_{\text{AA}}(x) = \frac{\alpha^\alpha}{\Gamma(\alpha)} x^{\alpha - 1} e^{-\alpha x} \]

\[ x = \frac{\Delta p_T}{\langle \Delta p_T \rangle} \]

\[ \langle \Delta p_T \rangle = \beta p_T^\gamma \log(p_T) \]

Markov chain Monte Carlo to sample parameters based on uniform prior distributions

200K samplings
Jet energy loss: single inclusive jet
Jet energy loss: $\gamma +$ jet
Single jet versus $\gamma$-jet
Few out-of-cone scatterings

<table>
<thead>
<tr>
<th></th>
<th>Single inclusive jet in Pb+Pb</th>
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<tbody>
<tr>
<td></td>
<td>(0-10%) 2.76 TeV</td>
<td>(20-30%) 2.76 TeV</td>
<td>(0-10%) 5.02 TeV</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$3.87 \pm 2.93$</td>
<td>$4.47 \pm 2.83$</td>
<td>$4.41 \pm 2.86$</td>
</tr>
<tr>
<td></td>
<td>$(1.45 \pm 0.01)$</td>
<td>$(1.33 \pm 0.02)$</td>
<td>$(1.58 \pm 0.02)$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$1.40 \pm 1.12$</td>
<td>$1.12 \pm 0.47$</td>
<td>$1.06 \pm 0.97$</td>
</tr>
<tr>
<td></td>
<td>$(1.39 \pm 0.06)$</td>
<td>$(1.08 \pm 0.07)$</td>
<td>$(1.56 \pm 0.06)$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$0.21 \pm 0.09$</td>
<td>$0.15 \pm 0.07$</td>
<td>$0.26 \pm 0.06$</td>
</tr>
<tr>
<td></td>
<td>$(0.21 \pm 0.01)$</td>
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<td>$(0.23 \pm 0.01)$</td>
</tr>
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|                      | $\gamma$-triggered jet in Pb+Pb |                |                |
|                      | (0-30%) 2.76 TeV                | (30-100%) 2.76 TeV | (0-30%) 5.02 TeV |
| $\alpha$             | $2.13 \pm 1.28$                | $3.75 \pm 2.81$ | $0.90 \pm 0.09$ |
|                      | $(1.95 \pm 0.12)$              | $(1.04 \pm 0.06)$ | $(1.84 \pm 0.13)$ |
| $\beta$              | $2.68 \pm 1.40$                | $0.55 \pm 0.44$ | $1.50 \pm 0.85$ |
|                      | $(0.72 \pm 0.06)$              | $(0.53 \pm 0.04)$ | $(0.50 \pm 0.04)$ |
| $\gamma$             | $0.16 \pm 0.14$                | $0.13 \pm 0.18$ | $0.21 \pm 0.12$ |
|                      | $(0.44 \pm 0.02)$              | $(0.30 \pm 0.02)$ | $(0.56 \pm 0.02)$ |

TABLE I. Parameters [$\alpha, \beta, \gamma$] of the jet energy loss distribution from Bayesian fits to single inclusive and $\gamma$-triggered jet spectra in Pb+Pb collisions at $\sqrt{s} = 2.76$ and 5.02 TeV. Numbers in parentheses are from fits to LBT results.
Summary

• Jet energy loss influenced by transport shower partons, medium response & radial flow
• Jet suppression is influenced by many competing efforts
• Jet energy loss distribution has a scaling behavior
• Extracted jet energy loss with pt dependence
• Jet energy loss caused by rare out-of-cone scattering in an expanding medium
backups
Jet cross section in p+p and A+A

\[ \frac{d\sigma_{\text{jet}}}{dp_T d\eta} = \sum_{a,b,c} d\sigma_{ab}^c \otimes J_c(p_T, p_{Tc}, R) \]

Kang, Ringer & Vitev, PLB769(2017)242

Medium modified jet function and jet energy loss distribution:

\[ \tilde{J}_c(p_T, p_{Tc}, R, r, b) = \int d\Delta p_T w_c(\Delta p_T, p_T, R, r, b, \phi) J_c(p_T + \Delta p_T, p_{Tc}, R) \]

\[ W_{AA}^c(\Delta p_T, p_T, R) = \frac{\int d^2r d^2b t_A(r) t_A(\|b - r\|) \frac{d\phi}{2\pi} w_c(\Delta p_T, p_T, R, r, b, \phi)}{\int d^2r d^2b t_A(r) t_A(\|b - r\|)} \]

Medium modified jet production cross section

\[ \frac{d\sigma_{\text{jet}}^{AA}}{dp_T dy} = \int d\Delta p_T \sum_{a,b,c} W_{AA}^c(\Delta p_T, p_T + \Delta p_T, R) d\sigma_{ab}^c \otimes J_c(p_T + \Delta p_T, p_{Tc}, R) \]
Jet energy loss and $\gamma(Z^0)$-jet asymmetry

Luo, Cao, He & XNW, PLB782(18)707

Zhang, Luo, XNW, Zhang, PRC98(2018)021901
Effects of medium response

Chen, Cao, Luo, Pang, XNW, PLB777(2018)86

Luo, Cao, He & XNW, PLB782(18)707
Energy dependence of jet spectra

The graph shows the energy dependence of jet spectra, with the 

$d^2 / d p_T dy (\text{nb/GeV})$ 

variable plotted against $p_T$ (GeV) on the y-axis and $d^2 / d p_T dy$ (nb/GeV) on the x-axis. The curves represent different values of $|y|$, where $|y| < 0.3$, $|y| < 0.8$, $|y| < 1.2$, and $|y| < 2.1$. The graph includes data points for $|s_{\text{NN}}| = 5.02 \text{ TeV}$ and $|s_{\text{NN}}| = 2.76 \text{ TeV}$.
Groomed jet splitting function & mass

Medium response do not influence groomed jet splitting function
Medium response increases the groomed jet mass

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$