Studies of the difference between light and heavy flavor energy loss by reconstructed jets

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with F. Senzel, J. Uphoff and C. Greiner
based on arXiv:1602.05086

Hard Probes 2016
Heavy flavor puzzle: no mass hierarchy?

Nuclear modification factor

\[ R_{AA} = \frac{d^2N_{AA}/dp_t\,dy}{N_{bin} \, d^2N_{pp}/dp_t\,dy} \]

light flavor

heavy flavor

Uphoff, FS, Fochler, Wesp, Xu, Greiner


Uphoff, Fochler, Xu, Greiner

Nowadays: Jet reconstruction in heavy-ion collisions!

by M. van Leeuwen

clustering particles with

$$\Delta R = \sqrt{\Delta \phi^2 + \Delta y^2} < R$$

inclusive jets

ALICE collaboration

ATLAS collaboration

beauty-tagged jets

CMS collaboration

CMS collaboration
\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

PbPb, 150 \text{ \mu b}^{-1}
pp, 5.3 \text{ pb}^{-1}

pQCD: PLB 726 (2013) 251-256

ALICE collaboration

ATLAS collaboration

CMS collaboration

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Studies of jets within BAMPS

Hard Probes 2016
Our question:
What can we learn about the different energy loss mechanisms of light flavor and heavy flavor partons by studying reconstructed jets in heavy-ion collisions?
The partonic transport model BAMPS

\[ \text{BAMPS} \equiv \text{Boltzmann Approach to Multi-Parton Scattering} \]

Numerically solving the (3+1)D Boltzmann transport equation for partons on the mass-shell:

\[ \frac{\partial f}{\partial t} + \frac{\mathbf{p}}{E} \frac{\partial f}{\partial \mathbf{r}} = C_{2 \rightarrow 2} + C_{2 \leftrightarrow 3} \]

- Massless particles (gluons & quarks)
- Discretized space \( \Delta V \) and time \( \Delta t \):

\[ P_{2 \rightarrow 2} = v_{\text{rel}} \sigma_{2 \rightarrow 2} \frac{\Delta t}{\Delta V} \quad P_{2 \rightarrow 3} = v_{\text{rel}} \sigma_{2 \rightarrow 3} \frac{\Delta t}{\Delta V} \]

- Test-particles ansatz \( N_{\text{test}} \)

BAMPS in a nutshell - elastic and radiative processes

**Screened leading-order pQCD**

\[ |\mathcal{M}_{X\rightarrow Y}|^2 \sim \frac{\alpha_s^2(t)}{[t - \kappa m_D^2(\alpha_s(t))]} \]

**Improved Gunion-Bertsch approx.**

\[ |\mathcal{M}_{X\rightarrow Y+g}|^2 \sim |\mathcal{M}_{X\rightarrow Y}|^2 \times \alpha_s(q_t^2, k_t^2) P_g(q_t, k_t, y, \phi, M) \]


**Improved Gunion-Bertsch matrix element**

\[ |\overline{M}_{X \rightarrow Y + g}|^2 = |\overline{M}_{X \rightarrow Y}|^2 \times 48\pi\alpha_s (1 - \bar{x})^2 \]

\[ \times \left[ \frac{k_{\perp}}{k_{\perp}^2 + x^2M^2} + \frac{q_{\perp} - k_{\perp}}{(q_{\perp} - k_{\perp})^2 + m_D^2(\alpha_s) + x^2M^2} \right]^2 * \]

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**2 → 3 processes**

- \( g g \rightarrow g g g \)
- \( q g \rightarrow q g g \) and \( \bar{q} g \rightarrow \bar{q} g g \)
- \( q\bar{q} \rightarrow q\bar{q} g \)
- \( q q \rightarrow q q g \) and \( \bar{q} \bar{q} \rightarrow \bar{q} \bar{q} g \)
- \( q\bar{q}' \rightarrow q\bar{q}' g \) and \( \bar{q} \bar{q}' \rightarrow \bar{q} \bar{q}' g \)

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*with \( \bar{x} = k_{\perp} e^{\gamma} / \sqrt{s} \)*

**Issue**

Coherence effects within a *semi-classical* approach are not trivial.

**Effective implementation**

Parent parton is not allowed to scatter before emitted gluon is formed:

\[ |\mathcal{M}_{2\rightarrow3}|^2 \rightarrow |\mathcal{M}_{2\rightarrow3}|^2 \Theta (\lambda - X_{\text{LPM}} \tau_f) \]

- \( X_{\text{LPM}} = 0 \): No LPM suppression
- \( X_{\text{LPM}} = 1 \): Only independent radiations (forbids too many emissions)
- \( X_{\text{LPM}} \in (0; 1) \): Allows effectively some collinear gluon radiations
Modeling jets within BAMPS collisions

PYTHIA 6.4

Elliptic flow $v_2$

Shear viscosity $\eta/s$


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Comparable suppression of inclusive and b-tagged jets.

Pure pQCD elastic collisions are too weak for b-tagged jets.
Jet size $R$ dependence of jet suppression

- Inclusive and b-tagged jet $R_{AA}$ show different $R$ dependence.
- Decreasing $R$ shows less b-tagged jet suppression.

Pb+Pb, $\sqrt{s}=2.76$ TeV
running $\alpha_s$, $X_{LPM}=0.3$
$b=3.6$ fm
$|y|<2.0$
anti $k_t$

Z. Xu (Tsinghua University)
The partonic transport model BAMPS

Picture behind the $R$ dependence of jet suppression

PYTHIA

PYTHIA + medium transport

PYTHIA + medium transport + med.ind.radiation
Differential jet shape

\[ \rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \sum_{\text{particles} \in [r_a, r_b)} \frac{p_T^{\text{track}}}{p_T^{\text{jet}}} \]

jet shape \( \rho(r) \):

"fraction of reconstructed jet momentum between \( r - \delta r/2 \) and \( r + \delta r/2 \) around the jet axis."
Jet shapes in a heavy-ion collision

- Effects are indeed visible in the different jet shapes.
- b-tagged jet shapes will provide information about HQ processes.
Conclusions

- Reconstructing jets provide means for studying the energy loss of hard probes in heavy-ion collisions.
- Suppression of light and heavy flavor jets is comparable.
- Transport of PYTHIA gluons out of jet cones dominates the suppression of b-tagged jets.
- Jet shapes may be able to discriminate between different underlying energy loss mechanisms.

Future plans:

- How does a revisited modeling of the LPM effect change the energy loss and its path-length dependence?
- More systematic comparisons with data . . .
Backup slides
**Investigated scenarios for the E-loss of b-tagged jets**

<table>
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<th>scenario</th>
<th>heavy quarks</th>
<th>parton shower</th>
<th>HQ</th>
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BAMPS in a nutshell - dead cone effect

**Heavy quark suppression factor**

\[ D = \frac{1}{\left(1 + \frac{M^2}{\theta^2 E^2}\right)^2} = \frac{1}{\left(1 + \frac{\theta_D^2}{\theta^2}\right)^2} \]


**Dead cone effect in BAMPS**

While original dead cone effect is limited to a kinematical region, dead cone effect in BAMPS is valid in total phase space.

Momentum imbalance $A_J$ of reconstructed di-jets

**Definition**

$$A_J = \frac{p_t;\text{Leading Jet} - p_t;\text{Subleading Jet}}{p_t;\text{Leading Jet} + p_t;\text{Subleading Jet}}$$

**Graphical Data**

- $A_J \rightarrow 0$ balanced leading jet momenta
- $A_J \rightarrow 1$ unbalanced leading jet momenta

**Simulations**

- PYTHIA, w. smearing
- BAMPS, w. recoil+back.sub.
- BAMPS, w/o. recoil+back.sub.
- CMS, Pb+Pb 2.76TeV 0-10%
- CMS, p+p 2.76 TeV

**Parameters**

- $b = 3.4$ fm
- Anti-$k_t$, $R=0.3$
- $p_{t;1} > 120$ GeV
- $p_{t;2} > 30$ GeV
- $\Delta \phi > 2 \pi/3$
- $\sigma = 2.3 \sqrt{p_t}$
Screened matrix elements

\[ e.g. \ |\mathcal{M}_{qQ \to qQ}|^2 = \frac{64}{9} \pi^2 \alpha_s^2 \left( \frac{(M^2 - u)^2 + (s - M^2)^2 + 2M^2 t}{[t - \kappa m_D^2(\alpha_s)]^2} \right) \]

with \[ m_D^2(\alpha_s) = d_G \pi \alpha_s \int \frac{d^3p}{(2\pi)^3} \frac{1}{p} \left( N_c f_g + N_f f_q \right) \]

LO pQCD cross-sections

- \( gg \to gg \)
- \( gg \to q\bar{q} \)
- \( q\bar{q} \to gg \) and \( q\bar{q} \to q'\bar{q}' \)
- \( qg \to qg \) and \( \bar{q}g \to \bar{q}g \)
- \( q\bar{q} \to q\bar{q} \)
- \( qq \to qq \) and \( \bar{q}\bar{q} \to \bar{q}\bar{q} \)
- \( qq' \to qq' \) and \( \bar{q}\bar{q}' \to \bar{q}\bar{q}' \)

Running coupling evaluated at the microscopic scale

2 → 2 processes
\[ \alpha_s \to \alpha_s(Q^2), \quad Q^2 \in \{s, t, u\} \]

2 → 3 processes
\[ \alpha_s \to \alpha_s(Q^2), \quad Q^2 \in \{k_t^2, q_t^2\} \]

Remark
Due to universality arguments [1], the running coupling can be limited by
\[ \alpha_s;_{\text{max}} = 1.0. \]

Jet momentum loss underlying the suppression in HIC

\[ f(x) = A \log(x) + B \]

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