Flavor aspects of parton energy loss

Martin Spousta

Charles University in Prague

M.S., Brian Cole, EPJC 76 (2016) no.2 50
M.S., arXiv:1606.00903
+ new
Inclusive jet $R_{AA}$

Features:
1) only modest (if any) rise with increasing jet $p_T$, 

PRL 114 (2015) 072302
arXiv:1609.05383
Inclusive jet $R_{AA}$

Features:
1) only modest (if any) rise with increasing jet $p_T$,
2) almost no rapidity dependence
Charged particle $R_{AA}$

Features:
1) steep increase for $p_T > 10$ GeV
2) almost no rapidity dependence

EPJC 72 (2012) 1945
PLB 720 (2013) 52
JHEP09 (2015) 050
Charged particles in jets

Features:

1) enhancement of soft particles, depletion at intermediate $\xi$ (or $z$)
2) enhancement at high $z$ (low $\xi$)
Jets and charged particles – some basic questions

• Why do have the jet and charge particle $R_{AA}$ almost no rapidity dependence given quite different input parton spectra and flavor composition at different rapidities?

• What is responsible for the enhancement at high $z$ seen in the fragmentation?

• Can we find connection among charged particle $R_{AA}$, jet $R_{AA}$ and jet fragmentation?
Jets and charged particles – some basic questions

• Why do have the jet and charge particle $R_{AA}$ almost no rapidity dependence given quite different input parton spectra and flavor composition at different rapidities?

• What is responsible for the enhancement at high $z$ seen in the fragmentation?

• Can we find connection among charged particle $R_{AA}$, jet $R_{AA}$ and jet fragmentation?

→ Use a simple model with minimal assumptions on the quenching physics to extract basic properties of the jet quenching
The simplest modeling of parton energy loss

\[ \frac{dN}{dp_T^{jet}} = A \left[ f_{q0} \left( \frac{pT_0}{p_T^{jet}} \right)^{n_q} + (1 - f_{q0}) \left( \frac{pT_0}{p_T^{jet}} \right)^{n_g} \right] \]

- Jet spectra parameterized by a power law
- Fraction of jets of a given flavor (i.e. quark or gluon initiated)

\[ f_q \left( p_T^{jet} \right) = \frac{1}{1 + \left( \frac{1-f_{q0}}{f_{q0}} \right) \left( \frac{pT_0}{p_T^{jet}} \right)^{n_g-n_q}} \]
The simplest modeling of parton energy loss

\[ \frac{dn_{Q}(p_{T}^{\text{jet}})}{dp_{T}^{\text{jet}}} = \frac{dn\left(p_{T}^{\text{jet}} + S(p_{T}^{\text{jet}})\right)}{dp_{T}^{\text{jet}}} \times \left(1 + \frac{dS}{dp_{T}^{\text{jet}}}\right) \]

Yield of quenched jets of a given flavor at given pt

\[ S_q \equiv s p_T \]

\[ S_g = c_F \times S_q \]

Fractional energy loss

\[ R_{AA} = f_q \left(\frac{1}{1 + S_q/p_T^{\text{jet}}}\right)^{n_q} \times \left(1 + \frac{dS_q}{dp_T}\right) + \]

\[ (1 - f_q) \left(\frac{1}{1 + S_g/p_T^{\text{jet}}}\right)^{n_g} \times \left(1 + \frac{dS_g}{dp_T}\right) \]
Jet $R_{AA}$ in the simplest model

Centrality vs. Rapidity

$R_{AA}$ as a function of $p_T$ for different centrality classes and rapidities.
Jet $R_{AA}$ in the simplest model

The simplest model does not work …
The simplest model does not work ... why?

→ jet spectra are not a simple power low
→ fractional energy loss is not realized in the nature
Extending the model

\[
\frac{dn}{dp_T^{jet}} = A \left( \frac{p_T^0}{p_T^{jet}} \right)^{n+\beta \log \left( \frac{p_T^{jet}}{p_T^0} \right)}
\]

More precise parameterization of input jet spectra

More general modeling of jet energy loss

\[
S = s' \left( \frac{p_T^{jet}}{p_T^0} \right)^\alpha
\]
Jet $R_{AA}$ in extended model
Flatness and no rapidity dependence of jet $R_{AA}$ are due to different energy loss of quark and gluon initiated jets.
Jet $R_{AA}$ in extended model

$->$ Flatness and no rapidity dependence of jet $R_{AA}$ are due to different energy loss of quark and gluon initiated jets
Quantifying the parton energy loss (I.)

Energy loss parameterized = encapsulated into two free parameters

\[ S = s' \left( \frac{p_T^{\text{jet}}}{p_T^0} \right)^\alpha \]
Quantifying the parton energy loss (I.)

Energy loss parameterized = encapsulated into two free parameters

\[ S = s' \left( \frac{p_T^{\text{jet}}}{p_T^0} \right)^{\alpha} \]

Quark with \( p_T = 40 \text{ GeV} \) (\( p_{T,0} \)) looses \( \sim 5 \text{ GeV} \).

100 GeV quark looses 8 GeV

Effective power \( \sim 0.55 \)
Quantifying the parton energy loss (I.)

Energy loss parameterized = encapsulated into two free parameters

\[ S = s' \left( \frac{p_T^{\text{jet}}}{p_T^0} \right)^{\alpha} \]

Quark with \( p_T = 40 \text{ GeV} \) (\( p_T^0 \)) looses \( \sim 5 \text{ GeV} \).

100 GeV quark looses 8 GeV

Energy loss does not extrapolate to zero. Hot medium even in peripheral? Some other physics? (nPDFs?, limits of Glauber?, …)

Effective power \( \sim 0.55 \)

Linear dependence of \( s' \) on \( N_{\text{part}} \)
Predictions for 2.76 TeV

$\rightarrow$ Forward should exhibit a decrease of $R_{AA}$
–> If the jet quenching is the same at 2.76 and 5 TeV, the jet $R_{AA}$ will be very similar to that measured at 2.76 TeV
$b$-jets

$R_{AA}$

$0-100\%$

$R_{AA}$

$p_{T,jet} = 90-110$ GeV

$R_{AA}$

$\rightarrow b$-jets are suppressed more than light-quark jets

$\rightarrow$ more precise data needed to quantify by how much

same parameters as for light jets
Modifications of fragmentation functions


hardest resolved next-to-hardest soft fragments

... color coherence likely very important in the quenching physics

Figure from

Modifications of fragmentation functions

\[-\] Subtract the energy from the jet / initial parton and then let it fragment as in the vacuum
Modifications of fragmentation functions

→ Subtract the energy from the jet / initial parton and then let it fragment as in the vacuum

(Ratio of fragmentation functions)
Modifications of fragmentation functions

→ Subtract the energy from the jet / initial parton and then let it fragment as in the vacuum

→ Structure seen at intermediate and high-z is due to the difference in quenching of quark and gluon initiated jets

→ Direct verification of a presence of color coherence effects in the data
Modifications of fragmentation functions – prediction

... central rapidity – higher yields at high-z (but not by much)

![Graph showing the ratio of $R_D(z)$ for different rapidity intervals. The graph indicates an increase in ratio for high-absolute-value rapidities at high-z, with the increase being more pronounced for smaller rapidity intervals.](image-url)
Modifications of fragmentation functions – prediction

... central rapidity – higher yields at high-z (but not by much)
Modifications of fragmentation functions – prediction

... central rapidity – higher yields at high-z (but not by much)
Modifications of fragmentation functions – a detail

Excess of low-z not due to flavor effects (maybe due to in-cone radiation, recoil, collective response, …)
Modifications of fragmentation functions – a detail

Excess of low-z not due to flavor effects (maybe due to in-cone radiation, recoil, collective response, ...)  

- These low-z hadrons contribute to the measured jet energy. Parameter $s'$ contains this soft part.
- Soft part contributes to the measured fragmentation via denominator of $z$.

$$p_{\text{measured}} = p_{\text{quenched}} + p_{\text{soft}}$$

![Graph showing $R_{b(z)}$ for ATLAS 0-10%, MC, and analytic models.](image)
Modifications of fragmentation functions – a detail

Excess of low-z not due to flavor effects (maybe due to in-cone radiation, recoil, collective response, ...)

- These low-z hadrons contribute to the measured jet energy. Parameter $s'$ contains this soft part.

- Soft part contributes to the measured fragmentation via denominator of $z$.

Contribution of soft hadrons to the jet energy can be estimated from the measurement at low-z => fragmentation distributions w/ correct soft contribution

\[ p_{\text{measured}} = p_{\text{quenched}} + p_{\text{soft}} \]
Modifications of fragmentation functions – a detail

\[ p_{T,\text{jet}}^{\text{measured}} = p_{T,\text{jet}}^{\text{quenched}} + p_{T}^{\text{soft}} \]

\[ R_{D}(z) \]

\[ \bullet \text{ ATLAS 0-10\%} \]

- Prediction: detailed measurement of fragmentation at the highest-z (or lowest-\(\xi\)) should exhibit a depletion
From jet internal structure to charged particle $R_{AA}$

Each particle of a given $p_T$ must be in a jet of the same or higher $p_T$

$\Rightarrow$ Charged particle $R_{AA}$ (at high-$p_T$) = convolution of flavor dependent jet suppression and fragmentation functions
From jet internal structure to charged particle $R_{AA}$
From jet internal structure to charged particle $R_{AA}$

High-$p_T$ jets are more suppressed than charged particles – a puzzle?
High-$p_T$ jets are more suppressed than charged particles – a puzzle?
– No, it is the same puzzle as the excess in $D(z)$ at high $z$.
The charged particle $R_{AA}$ (at high-$p_T$) = convolution of flavor dependent jet suppression and fragmentation functions.
From jet internal structure to charged particle $R_{AA}$

... we should not do this kind of plots – it is misleading
Flavor sensitivity

**Definition:** Flavor sensitivity = sensitivity of a given observable to the flavor (and spectra) of the initial parton leading to a possible incorrect interpretation of that observable.

**Example:** fragmentation functions at intermediate $z$ and high $z$, charged particle $R_{AA}$

=> Checking other observables
Dijet asymmetry

**ATLAS** Preliminary
anti-$k_t$ $R = 0.4$ jets, $\sqrt{s_{NN}} = 2.76$ TeV

\[ \frac{1}{N} \frac{dN}{dx} \]

$100 < p_T < 126$ GeV  
0 - 10 %

- **Pb+Pb**
- **$pp$**

\[ x_J = \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}}} \]
Dijet asymmetry

$\rightarrow$ Measured asymmetry is not due to different quenching of q/g jets.

$\rightarrow$ NLO generators may start to be important (shape matches w/ data).
Dijet asymmetry

→ The subleading jet is quenched very differently than the leading jet → quantify

→ The subleading jet in the maximum of the $x_J$ is suppressed by a factor of $\sim 3$ larger than the leading jet
Jet substructure using splitting

Splitting, $z_g$ – defined by the 'Soft Drop' algorithm (used in pp studies of boosted objects):

- Run C/A algorithm in the jet
- Compare subjets; if

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} < 0.1$$

- drop the softer partner and repeat the same calculation with two "parents" of harder subject; else

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} = z_g$$
Jet substructure using splitting

→ Jets with a distinct subject structure ($p_{T1}$ closer to $p_{T2}$) quenched more (or more jets with less splitting)

→ Looks significant, but the change involves only 5-10% of jets
Jet substructure using splitting

Use the quenching model in the same way as before for the fragmentation
Jet substructure using splitting

Modification not due to a simple flavor bias ...

... since $z_g$ does not depend much on the flavor or jet $p_T$
Puzzling difference between RHIC and LHC

- Andrés et. al (EPJ C76 (2016) 475) … K factor 2-3 times larger at RHIC than at the LHC, with only mild centrality dependence,…

- Horowitz, Gyulassy (Nucl.Phys. A872, 265) … suppression at RHIC is larger

=> How is the extraction of the quenching from charged particles influenced by the underlying parton/jet kinematics?
• Jets very different between LHC and RHIC
• Jet spectra for a given flavor more steep at RHIC
• Flavor composition also different

→ Will impact charged particle $R_{AA}$

→ Apply the effective quenching factors extracted at the LHC to RHIC jets
Charged particle $R_{AA}$
RHIC vs LHC

- Effective quenching factors from LHC applied to RHIC parton/jet spectra
- Same quenching leads to smaller $R_{AA}$ in the case of RHIC

=> Initial parton spectra and flavor composition are crucial for the extraction of the size of jet quenching
Flavor sensitivity

**Definition:** Flavor sensitivity = sensitivity of a given observable to the flavor (and spectra) of the initial parton leading to a possible incorrect interpretation of that observable.

**Flavor sensitive:** jet $R_{AA}$, fragmentation functions at intermediate $z$ and high $z$, charged particle $R_{AA}$

**Likely flavor sensitive:** jet width, jet mass, single particles

**Almost flavor insensitive:** $z_g$ distribution, $x_J$ distribution, fragmentation at low $z$ (= high $\xi$)
Quantifying the parton energy loss (II.)

\[
\frac{dn_Q(p_T^{\text{jet}})}{dp_T^{\text{jet}}} = \frac{dn \left( p_T^{\text{jet}} + S(p_T^{\text{jet}}) \right)}{dp_T^{\text{jet}}} \times \left( 1 + \frac{dS}{dp_T^{\text{jet}}} \right)
\]

Yield of quenched jets of a given flavor at given pt

\[ S_q = s' \left( \frac{p_T^{\text{jet}}}{p_T,0} \right)^\alpha \]
\[ S_g = c_F \times S_q \]

- So far \( \alpha \) and \( s' \) free, \( c_F=9/4 \) fixed
- \( c_F=9/4 \) … difference in the probability to radiate a gluon from a gluon and quark source in the vacuum in large \( Q^2 \) limit or soft limit
- Vacuum value of \( c_F \) measured and calculated in pQCD (MLLA)
Quantifying the parton energy loss (II.)

- So far $a$ and $s'$ free, $c_F = 9/4$ fixed
- $c_F = 9/4$ ... difference in the probability to radiate a gluon from a gluon and quark source in the vacuum in large $Q^2$ limit or soft limit
- Vacuum value of $c_F$ measured and calculated in pQCD (MLLA)
Quantifying the parton energy loss (II.)

- So far $a$ and $s'$ free, $c F = 9/4$ fixed
- $c F = 9/4$ ... difference in the probability to radiate a gluon from a gluon and quark source in the vacuum in large $Q^2$ limit or soft limit
- Vacuum value of $c_F$ measured and calculated in pQCD (MLLA)

- NLLA limit, $r = C_A/C_F = 2.25$
- $c_F = 1.7 - 1.8$ for $Q = 20 - 100$ GeV
Quantifying the parton energy loss (II.)

\[ S_q = s' \left( \frac{P^\text{jet}_{T}}{P^0_{T}} \right)^\alpha \]

\[ S_g = c_F \times S_q \]

- Use rapidity differential jet \( R_{AA} \) measurement to perform a multidimensional fit and extract \( \alpha \), \( s' \) and \( c_F \) simultaneously.

- Input spectra @ NLO (POWHEG+PYTHIA8 + 3 variations of PDFs)

\[ s' = x \cdot N_{\text{part}} + y \]

\[ x = 12.3 \pm 1.4 \text{ GeV}, \]
\[ y = 1.5 \pm 0.2 \text{ GeV} \]

\[ \alpha = 0.52 \pm 0.02 \]

\[ c_F = 1.78 \pm 0.12 \]

\[ \rightarrow \text{value of } c_F \text{ consistent with the value in the vacuum} \]
What about other objects?

Data tell us that the medium largely sees a jet as one object => what about other objects with a structure that are suppressed?
What about other objects?

Data tell us that the medium largely sees a jet as one object
=> what about other objects with a structure that are suppressed?
What about other objects?

Data tell us that the medium largely sees a jet as one object
=> what about other objects with a structure that are suppressed?

\[ J/\Psi \ & \ \Psi(2S) \]
What about other objects?

Data tell us that the medium largely sees a jet as one object
=> what about other objects with a structure that are suppressed?

\[ J/\Psi \quad \& \quad \Psi(2S) \]

... check the differences between the suppression of jets and charmonia at high-\( p_T \) (at the LHC at mid-rapidity)

Input:

- Measured pp spectra of charmonia (cannot rely on out of the box PYTHIA or other generator)
- Energy loss extracted from jets
Charmonia

Graph 1: $R_{AA}^{J/\psi}$ for $|y|<2.4$ and $6.5 < p_T < 30$ GeV

Graph 2: $R_{AA}^{J/\psi}$ for $|y|<2.4$ and $6.5 < p_T < 30$ GeV

- Model - light quark
- Model - gluon

Data sources:
- CMS, JHEP 05, 063
- CMS PAS HIN-12-014
Charmonia

... suppression of both charmonia at $p_T > 6.5$ GeV is similar to the suppression of light quark jets
Summary

• Absence of rapidity dependence and flatness of jet $R_{AA}$, characteristic shapes of jet fragmentation at mid and high $z$ are due to flavor dependent jet quenching.

• Data say that coherence effects are important (medium largely, but not fully sees $R=0.4$ jets as one radiating object).

• Recoil (or in-cone radiation) modifies also measured high-$z$ fragmentation (same holds for all other observables).

• $b$-jets are quenched more than light quark jets.

• Dijet asymmetry: sub-leading jet is quenched $\sim 3$ times more than the leading jet.

• Charged particle $R_{AA}$ @ RHIC vs LHC: initial parton spectra and flavor composition are important for the extraction of the size of quenching (for the same quenching $R_{AA}$ at 200 GeV will be smaller than $R_{AA}$ at 2.76 TeV)
Summary (cont'd)

• Average jet quenching can be parameterized as follows

\[ s = x \cdot N_{\text{part}} + y \]

|x = 12.3 \pm 1.4 \text{ GeV},
|y = 1.5 \pm 0.2 \text{ GeV}|

|\alpha | 0.52 \pm 0.02 |
|\text{c}_F | 1.78 \pm 0.12 |

\[ S_q = s' \left( \frac{p_T^\text{jet}}{p_T^{0}} \right)^\alpha \]

(... can be used in simple modeling, checking observables, comparisons w/ full quenching models).

• Color factor, extracted for the first time in HI, seems not to be modified by the medium (c_F = 1.78 \pm 0.12).

• Parton energy loss does not extrapolate to 0 for N_{\text{part}} \to 0.

• Suppression of charmonia at p_T>6.5 GeV at midrapidity behaves like the suppression of light quark jets.
Backup slides
Flavor fractions and fit parameters

Fit type | Parameter | \(|y| < 2.1\) | \(|y| < 0.3\) | \(0.3 < |y| < 0.8\) | \(1.2 < |y| < 2.1\)
---|---|---|---|---|---
All | \(f_q\) | 0.34 | 0.28 | 0.29 | 0.40
Power law | \(n_q\) | 5.66 | 5.37 | 5.40 | 6.15
 | \(n_g\) | 6.25 | 5.97 | 6.09 | 6.92
Extended power law | \(n_q\) | 4.19 | 4.34 | 4.27 | 3.75
 | \(\beta_q\) | 0.71 | 0.49 | 0.54 | 1.2
 | \(n_g\) | 4.69 | 4.55 | 4.57 | 4.60
 | \(\beta_g\) | 0.80 | 0.71 | 0.76 | 1.2

The 7th International Conference on Hard and Electromagnetic Probes
D(z) parameterization

\[ D(z) = a \cdot \frac{(1 + dz)^b}{(1 + e z)^c} \cdot \exp(-f z) \]

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quark</td>
<td>318</td>
<td>2.51</td>
<td>1.44</td>
<td>-0.85</td>
<td>52.4</td>
<td>0</td>
</tr>
<tr>
<td>Gluon</td>
<td>574</td>
<td>1.87</td>
<td>2.32</td>
<td>9.09</td>
<td>32.0</td>
<td>10.3</td>
</tr>
</tbody>
</table>
\[ R_{AA} = f_q \left( \frac{1}{1 + S_q / p_T^{\text{jet}}} \right)^{n_q + \beta_q \log((p_T^{\text{jet}} + S_q) / p_T^{\text{T0}})} \]

\[ \times \left( \frac{p_{T0}^{\text{jet}}}{p_T^{\text{jet}}} \right)^{\beta_q \log(1 + S_q / p_T^{\text{jet}})} \left( 1 + \frac{dS_q}{dp_T^{\text{jet}}} \right) \]

\[ + (1 - f_q) \left( \frac{1}{1 + S_g / p_T^{\text{jet}}} \right)^{n_g \beta_g \log((p_T^{\text{jet}} + S_g) / p_T^{\text{T0}})} \]

\[ \times \left( \frac{p_{T0}^{\text{jet}}}{p_T^{\text{jet}}} \right)^{\beta_g \log(1 + S_g / p_T^{\text{jet}})} \left( 1 + \frac{dS_g}{dp_T^{\text{jet}}} \right) , \]

\[ f_q \left( p_T^{\text{jet}} \right) = \frac{1}{1 + \left( \frac{1 - f_{q0}}{f_{q0}} \right) \left( \frac{p_{T0}^{\text{jet}}}{p_T^{\text{jet}}} \right)^{n_g - n_q + (\beta_g - \beta_q) \log(p_T^{\text{jet}} / p_T^{\text{T0}})}} . \]
Minimization in (I.)

10-20%

60-70%
Modifications of fragmentation functions – a detail

How the soft excess is estimated:

\[ \Phi_{\text{inc}}^{\text{soft}} = f_q^{\text{int}} \Phi_q^{\text{soft}} + (1 - f_q^{\text{int}}) \Phi_g^{\text{soft}} \]

\[ \Phi_g^{\text{soft}} = c_F \Phi_q^{\text{soft}} \]

\[ D^{\text{meas}}(z) = f_q^{\text{int}} D_q(z[1 + \Phi_q^{\text{soft}}]) + (1 - f_q^{\text{int}}) D_g(z[1 + \Phi_g^{\text{soft}}]) \]
Charmonia in p+Pb
Feed down

ATLAS, JHEP 07 (2014) 154
ATLAS, JHEP 07 (2014) 154
Modifications of fragmentation functions

The 7th International Conference on Hard and Electromagnetic Probes