Effects of jet-medium interactions on angular correlations of jet-particle pairs at different energy scales

Martin Rohrmoser$^a$

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02/10/2018
Nuclear modification factor $R_{AA}$

$$R_{AA}(p_T) := \frac{N_{AA}(p_T)}{\langle T_{AA} \rangle \sigma_{pp}(p_T)}.$$ 

Collisional Energy Loss:

[Image of a graph showing the nuclear modification factor $R_{AA}$ as a function of $p_T$ with different models and ALICE data points.]

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Collisional & Radiative Energy Loss:

$\Delta E$

PbPb at $\sqrt{S_{NN}} = 2.76$ TeV

Centrality: 0-20%

ALICE D mesons ($|y|<0.5$)

WHDG

MC@SHQ+EPOS2+rad.+LPM

BAMPS rad.+el.

Vitev et al.

Djordjevic et al.

Duke

[EUR. PHYS. J. C76 (2016) 1-151]
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⇒ Need for more discriminative observables!

Collisional vs. Radiative Processes

Collisional:

\[ \Delta E \to R_{AA}, \]

i.e.: Observables for sets of individual particles

Different Two-Particle Correlations!

Study pairs of correlated particles! ⇔ Study Jets!
Collisional vs. Radiative Processes

Collisional:

\[ \Delta E \]

Radiative:

\[ \Delta E \implies R_{AA}, \]

i.e.: Observables for sets of individual particles

Different Two-Particle Correlations!

Study pairs of correlated particles! \iff Study Jets!
Descriptions of Jets in the Vacuum
Factorization and DGLAP evolution

Production of multiple partons: soft and/or collinear emissions dominant! \(\rightarrow\) They factorize:

\[
\sigma_{n+1} = \sigma_n \times \frac{Q^2}{1-\chi}.
\]

Number Distribution for particles: \(D(\chi, Q, m)\).

Probability density for splitting: \(P(\chi)\).

DGLAP equations:

\[
\frac{\partial D_i(x, Q, m)}{\partial \ln(Q^2)} \simeq \sum_j \int \frac{dz}{z} D_j\left(\frac{x}{z}, Q, m\right) P_{ij}(z).
\]
Production of multiple partons: soft and/or collinear emissions dominant! → They factorize:

\[ \sigma_{n+1} \] 

\[ \sigma_n \] 

\[ Q^2 \] 

\[ 1 - \chi \] 

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→ Monte-Carlo Simulation of DGLAP-equations for jets between scales: \( Q^\uparrow, E_{\text{ini}}, \text{and } Q^\downarrow \)
Applications and Limitations

Applications:
- Parton cascades from:
  - $e^+ + e^-$ collisions,
  - pp-collisions (final state radiation),
  started by an initial parton.
- Allows to extract correlated parton pairs
  $\rightarrow$ 2-particle correlations!

Limitations:
- $Q^\uparrow$, $E_{\text{ini}}$ dependencies: No PDFs, no hard initial process, no initial state radiation,
- No multiple jet events,
- $Q^\downarrow$ dependence: No hadronization model.

Conclusion? $\rightarrow$ need to fix $Q^\downarrow$! Use (IRC) stable observables!

Validation:
Models of Jet-Medium Interaction
Radiative model A

Using a basic assumption of the YaJEM-model:

Virtuality $Q$ increases in the medium over time $t$:

$$\frac{dQ^2}{dt} = \hat{q}_R(t)$$

$Q$ increase $\Leftrightarrow$ More parton splittings:

Implementation (steps $t \mapsto t + \Delta t$):

$$Q \mapsto \sqrt{Q^2 + \hat{q}_R \Delta t},$$
$$\vec{p} \mapsto \vec{p},$$
$$\Rightarrow E \mapsto \sqrt{E^2 + \hat{q}_R \Delta t}.$$

...extra radiation!
Collisional model B

Transport coefficients:

\[ \vec{A}(t) := -\frac{d}{dt} \langle \vec{p}_\parallel \rangle, \]

\( \text{drag force} \)

\[ \hat{q}_C(t) := \frac{d}{dt} \langle \vec{p}_\perp \rangle^2. \]

\( \text{(squared) transverse momentum transfers} \)

\( \text{stochastic} \)

Thermalized medium: relation between \( \vec{A} \) and \( \hat{q}_C \)

We use:

\[ \frac{\hat{q}_C}{\vec{A}} \approx 0.09 + 0.715 \frac{T}{T_C} \]


\[ \hat{q}_C \sim \frac{210}{1+53T} T^3 \]


Assumption: \( \hat{q}_C = \hat{q}_R \) & Temperature profile \( T(t) \) from EPOS2.

...energy transfer to the medium!
Effective Models of Jet-Medium Interaction

$\Delta \vec{p}_\parallel$  $\Delta \vec{p}_\perp$  

$Q : \uparrow$

$\Rightarrow$ family of models:

<table>
<thead>
<tr>
<th>model</th>
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Disadvantages: Simplifying assumptions; lack of microscopic interactions.

Advantage: Consistent framework for studying collisional and radiative mechanisms.
Effective Models of Jet-Medium Interaction

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\[ Q : \uparrow \]

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Jet shapes: $\rho(r)$

$$
\rho(r) := \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{\sum_{\text{trk} \in [r_a, r_b]} p_{\perp}^{\text{trk}}}{p_{\perp}^{\text{jet}}} , \quad r = \sqrt{\Delta \phi^2 + \Delta \eta^2} .
$$
Jet shapes: $\rho(r)$

$Q_\uparrow = E_{\text{ini}} = 200$ GeV,
$Q_\downarrow = 0.6$ GeV, vacuum
$||\vec{p}|| > 0.7$ GeV.

bars: CMS
$pp$
$pp$
$r$
$\rho$
$\rho$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
$10^{1}$
$0$
$0.2$
$0.4$
$0.6$
$0.8$
$1$

CMS: [CMS PAS HIN-16-020]

$p^{\text{trk}}_{\perp} > 3$ GeV
$p^{\text{trk}}_{\perp} < 3$ GeV
$p^{\text{trk}}_{\perp} < 2$ GeV
$0.7$ GeV < $p^{\text{trk}}_{\perp} < 1$ GeV

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Jet shapes: $\rho(r)$

$Q_{\uparrow} = E_{\text{ini}} = 200$ GeV, $Q_{\downarrow} = 0.6$ GeV, \textit{radiative} $\|\vec{p}\| > 0.7$ GeV.

bars: CMS

bars: Pb-Pb 0 − 10%

$\rho$:
- $p_{\text{trk}}^\perp > 3$ GeV
- $p_{\text{trk}}^\perp < 3$ GeV
- $p_{\text{trk}}^\perp < 2$ GeV
- $0.7$ GeV $< p_{\text{trk}}^\perp < 1$ GeV

CMS: [CMS PAS HIN-16-020]

...increased soft contributions!
Jet shapes: $\rho(r)$

$Q^\uparrow = E_{\text{ini}} = 200$ GeV, $Q^\downarrow = 0.6$ GeV, collisional $\parallel \vec{p} \parallel > 0.7$ GeV.

bars: CMS
Pb-Pb 0 − 10%

CMS: [CMS PAS HIN-16-020]

...enhancement at large $r$!
Jet shapes: $\rho(r)$

- $Q^\uparrow = E_{\text{ini}} = 200$ GeV,
- $Q^\downarrow = 0.6$ GeV, hybrid.
- $\|\vec{p}\| > 0.7$ GeV.

bars: CMS
Pb-Pb 0 − 10%

$\hat{q}$: MR 0.5

CMS: [CMS PAS HIN-16-020]

More on jet-structure:

- cf. Iurii Karpenko’s talk!

$p_{\perp} > 3$ GeV
$p_{\perp} < 3$ GeV
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$0.7$ GeV $< p_{\perp} < 1$ GeV

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Two-Particle Correlations
Angular Heavy-Light Particle Correlations

\[ \Delta \theta \]

light particle

Beam axis

Heavy quark

Beam axis
Discrimination via $\|\vec{p}\|_{\text{cut}}$

\[
\langle \Delta \theta \rangle \text{ [rad]}
\]

\begin{figure}
\centering
\begin{tikzpicture}
\begin{axis}[
    xlabel=$\|\vec{p}\|_{\text{cut}}$ [GeV],
    ylabel=$\langle \Delta \theta \rangle$ [rad],
    grid=major,
    legend style={at={(0.97,0.5)},anchor=north east},
    ]

\addplot[blue, thick]
    coordinates{(0,1.2)(2,1)(4,0.8)} node [pos=0.5, above] {vacuum}
        coordinate (vacuum_point); 
\addplot[red, dashed, thick]
    coordinates{(0,0.8)(2,0.6)(4,0.4)} node [pos=0.5, above] {0.5$\hat{q}$}
        coordinate (0.5q_point); 
\addplot[green, dotted, thick]
    coordinates{(0,0.4)(2,0.2)(4,0)(6,0)} node [pos=0.5, above] {$\hat{q}$}
        coordinate (hatq_point); 

\node [above] at (vacuum_point) {\text{vacuum}};
\node [above] at (0.5q_point) {0.5$\hat{q}$};
\node [above] at (hatq_point) {$\hat{q}$};

\end{axis}
\end{tikzpicture}
\end{figure}

$Q^+ = E_{\text{ini}} = 20$ GeV,
$Q^- = 0.6$ GeV,
\text{radiative.}
Discrimination via $\|\vec{p}\|_\text{cut}$

$\langle \Delta \theta \rangle$ [rad]

$0$.2 $0$.4 $0$.6 $0$.8 $1$ $1.2$

$0$ $2$ $4$

$\|\vec{p}\|_\text{cut}$ [GeV]

- vacuum
- $0.5\hat{q}$
- $\hat{q}$

$Q^\uparrow = E_{\text{ini}} = 20$ GeV,
$Q^\downarrow = 0.6$ GeV,
collisional.
Discrimination via $\|\vec{p}\|_{\text{cut}}$

$\langle \Delta \theta \rangle [\text{rad}]$

- Vacuum
- $0.5\hat{q}$
- $\hat{q}$

$Q^\uparrow = E_{\text{ini}} = 20 \text{ GeV},$
$Q^\downarrow = 0.6 \text{ GeV},$

hybrid.
Discrimination via $||\vec{p}||_{cut}$

$\langle \Delta \theta \rangle$ [rad] vs $||\vec{p}||_{cut}$ [GeV]

- vacuum
- radiative
- collisional
- hybrid, $0.5\hat{q}$

$Q_+ = E_{ini} = 20$ GeV,
$Q_- = 0.6$ GeV.
Summary

Key-Result:
Induced Radiation: Broadening at small energies.
Transverse forces: Broadening at all energies.

Main Conclusion:
Angular Heavy-Light particle correlations allow to distinguish different mechanisms of in-medium parton-energy loss!

To Do:
Hadronization↔jet-algorithms, heavy quark masses (cf. Dead-Cone effect), PDF’s, initial state radiation, hard initial collisions,...
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Thank you for your attention!