Modification of jet substructure in heavy ion collisions as a probe of the resolution length of quark-gluon plasma

Daniel Pablos

in collaboration with J. Casalderrey, G. Milhano & K. Rajagopal

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Motivation

Many new jet substructure measurements:

- differential
- groomed

Chance to explore underlying physical mechanisms with detail:

- phase space effects
- medium response
- QGP resolution length
The hybrid strong/weak coupling model

- Evolution of high virtuality energetic jets dominated by DGLAP evolution;

- Interaction of partons with QGP of $T \sim \Lambda_{QCD}$ is strongly coupled;

- Energy and momentum deposited in the QGP hydrodynamize quickly;
The hybrid strong/weak coupling model

Evolution of high virtuality energetic jets dominated by DGLAP evolution;
- Parton shower generated with PYTHIA8.
- Formation time argument for space-time picture.

Interaction of partons with QGP of $T \sim \Lambda_{QCD}$ is strongly coupled;
- Energy loss rate from holography:

$$\frac{1}{E_{\text{in}}} \frac{dE}{dx} = -4 \frac{x^2}{\pi x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}$$

$$x_{\text{stop}} = \frac{1}{2} \frac{E_{\text{in}}^{1/3}}{\kappa_{\text{SC}} T^{4/3}}$$

Energy and momentum deposited in the QGP hydrodynamize quickly;
- Compute modified hadron spectrum from perturbed freeze-out hyper-surface:

$$E \frac{d\Delta N}{d^3p} = \frac{1}{32\pi} \frac{m_T}{T^5} \cosh(y - y_j) \exp \left[ -\frac{m_T}{T} \cosh(y - y_j) \right] \left\{ p_T \Delta P_T \cos(\phi - \phi_j) + \frac{1}{3} m_T \Delta M_T \cosh(y - y_j) \right\}$$

Pablo et al. - JHEP '14, '16, '17

Chesler & Rajagopal - PRD '14, JHEP '16
The QGP Resolution Length

QGP resolution length:

minimal distance between two coloured charges such that they engage with the plasma independently.

The medium perceives a parton shower as a collection of effective probes.
The QGP Resolution Length

QGP resolution length:
minimal distance between two coloured charges such that they engage with the plasma independently.

At weak coupling:
connection between resolution length and energy loss.

At strong coupling:
no such connection (yet).

In the hybrid model:
resolution length proportional to the Debye screening length of QGP.

\[ L_{\text{res}} \sim \lambda_D \]
Two extreme scenarios

Look for sensitivity of observables to $L_{\text{res}}$:

Take two extreme values for $L_{\text{res}}$:

- $L_{\text{res}} = 0$ fully resolved case
- $L_{\text{res}} = \infty$ fully unresolved case

(explore realistic values later on)
Two extreme scenarios

Look for sensitivity of observables to $L_{\text{res}}$:

- Take two extreme values for $L_{\text{res}}$:
  - $L_{\text{res}} = 0$ fully resolved case
  - $L_{\text{res}} = \infty$ fully unresolved case

(choose realistic values later on)

Amount of jet quenching depends on $L_{\text{res}}$

- Adjust value of $\kappa_{\text{sc}}$ to compare results at the same value of jet RAA

$\kappa_{\text{sc}}$ range:

- $L_{\text{res}} = 0$ (global fit) 0.404 $< \kappa_{\text{sc}} < 0.423$
- $L_{\text{res}} = \infty$ (adjusted) 0.5 $< \kappa_{\text{sc}} < 0.52$

Relative suppression of hadrons vs jets strongly depends on QGP resolution length.

(see Pablos et al. - PRC '19 and Mehtar-Tani & Tywoniuk - PRD '18)
A frustrating observable: charged jet mass

Without wake:

\( L_{\text{res}} = 0 \)
shift towards smaller masses

\( L_{\text{res}} = \infty \)
barely any modification

Larger mass jets
are more active;
more suppressed if
substructure resolved.

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University of Bergen
A frustrating observable: charged jet mass

With wake:

Soft particles from the wake increase the mass, compensating quenching.

\[ L_{\text{res}} = 0 \quad \text{and} \quad L_{\text{res}} = \infty \]

barely distinguishable!

Surprisingly good description of data across three \( p_T \) ranges, after cancellation of effects…
Soft Drop (SD) procedure in a nutshell:

1. Reconstruct jet with anti-$k_T$.

2. Recluster jet with Cambridge-Aachen.

3. Go back clustering history, store $z$ and $\Delta R$ of each pair of branches.
Soft Drop (SD) procedure in a nutshell:

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If stop at first step that satisfies SD condition:

- **1st SD “splitting”**
  - study such 1st “splitting”
  - study groomed jet properties

**Soft Drop condition:**

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{cut} \left( \frac{R_{12}}{R_0} \right)^\beta$$
Soft Drop (SD) procedure in a nutshell:

1. Reconstruct jet with anti-$k_T$.
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If stop at first step that satisfies SD condition:
- 1st SD “splitting”
  - study such 1st “splitting”
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If count all “splittings” that satisfy SD condition: (following the hardest branch, i.e. Iterative SD)
- # SD “splittings”, $n_{SD}$

Frye et al. - JHEP ’17

Analytic Distributions

\begin{align*}
& p_T = 500 \text{ GeV}, \quad R = 0.6 \\
& z_{\text{cut}} = 0.007, \quad \beta = -1, \quad \theta_{\text{cut}} = 0
\end{align*}

- quark, NLL
- quark, LL
- gluon, NLL
- gluon, LL

\begin{align*}
\text{Probability} & \quad n_{SD} \\
0.5 & \quad 0.4 \\
0.3 & \quad 0.2 \\
0.1 & \quad 0.0 \\
0 & \quad 2 \quad 4 \quad 6 \quad 8 \quad 10
\end{align*}
# SD Splittings

**Flat grooming setup:**

\[
 z_{\text{cut}} = 0.1 \quad \beta = 0
\]

Remove soft & soft-collinear

\[
 L_{\text{res}} = 0
\]

reduction of \( n_{\text{SD}} \)

Wake negligible.

\[
 L_{\text{res}} = \infty
\]

barely any modification

Jets with higher multiplicity are more suppressed, ensemble biased towards less active ones if substructure is resolved.

(Also a subleading effect from "per jet" energy loss, see back-up)
1st SD splitting $z_g$ vs $\Delta R$

Strong ordering in $\Delta R$
(if parton shower resolved).

Larger $\Delta R$;
Larger phase-space for emissions;
Larger quenching, smaller survival rate;
(almost NO effect from “per jet” energy loss, see back-up)

$L_{\text{res}} = 0$
$L_{\text{res}} = \infty$

normalised to $N_{\text{jets}}$

(Not Sudakov safe, but results unchanged for $\beta = -\epsilon$)
1st SD splitting $z_g$ vs $\Delta R$

**Flat** $z_{cut} = 0.1$ $\beta = 0$

- **L_{res} = 0**
  - no wake, all $\Delta R$
  - no wake, $\Delta R < 0.1$
  - no wake, $\Delta R > 0.2$
  - all $\Delta R$

- **L_{res} = \infty**
  - $R = 0.4$, $80 < P_{T,jet} < 120$ GeV

Strong ordering in $\Delta R$
(if parton shower resolved).

- Larger $\Delta R$;
- Larger phase-space for emissions;
- Larger quenching, smaller survival rate;

(almost NO effect from "per jet" energy loss, see back-up)

**normalised to $N_{jets}$**

- Wake almost no effect.
- Negligible modification $z_g$ shape.

(not Sudakov safe, but results unchanged for $\beta = -\epsilon$)

(Daniel Pablos)
1st SD splitting $z_g$ vs $\Delta R$

**Flat** $z_{cut} = 0.1 \quad \beta = 0$

| $L_{res}$ = 0 | $L_{res}$ = $\infty$ |
|----------------|----------------------|
| no wake, all $\Delta R$ | no wake, all $\Delta R$ |
| no wake, $\Delta R < 0.1$ | no wake, $\Delta R < 0.1$ |
| no wake, $\Delta R > 0.2$ | no wake, $\Delta R > 0.2$ |

$R = 0.4$, $80 < P_{T, jet}^{ch} < 120$ GeV

- Quark vs Gluon jet effect more dominant here

- **RESOLVED**
- **UNRESOLVED**

$1/N_{jets} \frac{dN}{dz_g}$ (PbPb/pp)

- Normalised to $N_{jets}$
- Wake almost no effect.
- Negligible modification $z_g$ shape.

(Not Sudakov safe, but results unchanged for $\beta = -\epsilon$)

Strong ordering in $\Delta R$

(if parton shower resolved).

- Larger $\Delta R$;
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Daniel Pablos

University of Bergen
If shower resolved \rightarrow \text{increased weight of jets with smaller (groomed) mass.}

\textbf{White curves:} \text{lines of constant } \log\left(\frac{1}{(M_g/p_{T,g})}\right), \text{ where } \frac{M_g^2}{p_{T,g}^2} \approx z_g(1-z_g)\Delta R^2
Cutting the Lund Plane

Difference PbPb-pp of 1st SD splitting Lund plane

**Flat**
Removes soft & soft-collinear

**Core**
Removes soft-wide

**Soft-core**
Extends soft-collinear region

CMS angularity limit: $\Delta R > 0.1$
Cutting the Lund Plane

Difference PbPb-pp of 1st SD splitting Lund plane

- **Flat**
  - Removes soft & soft-collinear

- **Core**
  - Removes soft-wide

- **Soft-core**
  - Extends soft-collinear region
  - *Enhances Lund plane structure above $\Delta R > 0.1$*

CMS angularity limit: $\Delta R > 0.1$
Groomed jet mass

Not self-normalized:
merely reflect absence of wide angle configurations

Self-normalized:
differences due to $L_{\text{res}}$ of the size of the wake effect

Strong discriminating power,
not relying on the norm.
Low $z_g$ enhancement arises in our model from smearing effects.

Strong ordering in $\Delta R$ is robust under smearing effects. $L_{\text{res}} = \infty$ is disfavoured by data.

$z_g$ distribution, differential in $\Delta R$, successfully described by the Hybrid Model.
Low $z_g$ enhancement arises in our model from smearing effects. Strong ordering in $\Delta R$ is robust under smearing effects. $z_g$ distribution, differential in $\Delta R$, successfully described by the Hybrid Model. No enhancement of hard radiation.
Sensitivity to $L_{\text{res}}$

$\Delta R$ ordering of $z_g$ dist. closely correlated with value of QGP resolution length.

Results for $L_{\text{res}} = 2/\pi T$
closer to $L_{\text{res}} = 0$ than to $L_{\text{res}} = \infty$
Conclusions

- Studied the sensitivity of jet substructure observables to the value of the QGP resolution length:
  
  - Ungroomed observables too sensitive to soft particles from the wake (charged jet mass).
  - Groomed observables have a strong discriminating power:
    - Jet selection based on the properties of the 1st SD “splitting”;
    - Good taggers for the total amount of jet activity, which regulates quenching.
    - The smaller $L_{\text{res}}$, the larger the bias towards narrow configurations.
    - Different grooming setups give access to different phase space regions;
    - Proposed soft-core grooming to maximise discriminating power for groomed mass.

- Comparison between smeared theory & not unfolded data disfavours unresolved scenario.
  - Hybrid model describes very well the $z_9$ distribution, differential in $\Delta R$.
  - Questions power of observable to identify medium induced radiation or hard recoils.
Correlation between $n_{SD}$ and $\Delta R$

$80 < P_{T, jet}^{ch} < 120$ GeV

$R = 0.4$

$z_{cut} = 0.1, \beta = 0$
Correlation between $n_{SD}$ and $z_g$

$80 < P_{T,jet}^{ch} < 120$ GeV

$R = 0.4$

$z_{cut} = 0.1$, $\beta = 0$
A careful look into the selection bias

**Bias:** Increase # of low mult. jets
**E. loss:** Some branches below $z_{\text{cut}}$

**Restricted pp:** sample of pp jets from which the “surviving” sample of PbPb jets come from

**Bias:** Increase # of one-pronged jets
**E. loss:** Incoherent energy loss shift of $z_g$ (see Mehtar-Tani & Tywoniuk - JHEP ’17)
The role of formation time

Is wide configuration suppressed because formed early?

Radical test:
Assume all formation times are zero.

- Small adjustment of kappa.
- Almost no change in $\Delta R$ ordering.

Observable dominated by correlation between $\Delta R$ and multiplicity.
Wider jets lose more energy

*Wider, more active jets lose more energy than narrower, hard fragmenting ones*

Effect seen in the literature, for different models, on different observables

- Holographic “jets”
- JEWEL
- Hybrid Model

Even though each individual jet widens, the final distribution is narrower

Initial jet ensemble binned in energy and width

**CMS’ jet shapes ratio**

Brewer et al. - JHEP ’18
Wider, more active jets lose more energy than narrower, hard fragmenting ones

Effect seen in the literature, for different models, on different observables

Dijet asymmetry dominated by mass to momentum ratio, proxy for # vacuum splittings
Wider, more active jets lose more energy than narrower, hard fragmenting ones

Effect seen in the literature, for different models, on different observables

Larger R jets more quenched due to more energy loss sources