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

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Many new jet substructure measurements:

differential

mass

groomed



Chance to explore underlying physical mechanisms with detail:

- phase space effects
- medium response

QGP resolution length



Motivation

The hybrid strong/weak coupling model



Interaction of partons with QGP of T~ Λ_{QCD} is strongly coupled;

Energy and momentum deposited in the QGP hydrodynamize quickly;

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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~ Λ_{QCD} is strongly coupled;

Energy loss rate from holography:

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

Energy and momentum deposited in the QGP hydrodynamize quickly;

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

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- - Chesler & Rajagopal -PRD '14, JHEP '16

$$x_{
m stop} = rac{1}{2\kappa_{
m sc}} rac{E_{
m in}^{1/3}}{T^{4/3}}$$

 $\mathcal{O}(1)$ free parameter

- Compute modified hadron spectrum from perturbed freeze-out hyper-surface:

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 $-x^{2}$





The QGP Resolution Length

QGP resolution length:

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

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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.



J. Casalderrey et al. - 1210.7765

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

At strong coupling: no such connection (yet).

In the hybrid model:

resolution length proportional to the Debye screening length of QGP.

 $L_{\rm res}\sim\lambda_{\rm D}$

Hulcher et al. - JHEP '18





Two extreme scenarios

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

Take two extreme values for $L_{\rm res}$

(explore realistic values later on)

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

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Two extreme scenarios

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

Take two extreme values for $L_{\rm res}$

(explore realistic values later on)



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

Amount of *jet* quenching depends on L_{res}

Adjust value of κ_{sc} to compare results at the same value of jet RAA

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

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

1000

(see







A frustrating observable: charged jet mass



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Without wake:

 $L_{\rm res} = 0$ shift towards smaller masses

 $L_{\rm res} = \infty$ barely any modification

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



A frustrating observable: charged jet mass

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With wake:

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

 $L_{\rm res}=0$ and $L_{\rm res}=\infty$ 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 ΔR of each pair of branches.



Soft Drop



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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:



Soft Drop

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Larkoski et al. - JHEP '14, PRD '15

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- **1.** Reconstruct jet with anti- k_{T} .
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- 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}

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Soft Drop







Remove soft & soft-collinear

 $L_{\rm res} = 0$ reduction of n_{SD}

Wake negligible.

 $L_{\rm res} = \infty$

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)

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SD Splittings



1 st SD splitting z_g vs ΔR



normalised to N_{jets}

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

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Strong ordering in ΔR (if parton shower resolved). Larger ΔR ; Larger phase-space for emissions; Larger quenching, smaller survival rate; (almost NO effect from "per jet"





1 st SD splitting z_g vs ΔR



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- (not Sudakov safe, but results) unchanged for $\beta = -\epsilon$)
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- Negligible modification z_q shape.

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Strong ordering in ΔR (if parton shower resolved). Larger ΔR ; Larger phase-space for emissions; Larger quenching, smaller survival rate; (almost NO effect from "per jet" energy loss, see back-up)

(small incoherent energy loss effect visible at partonic level, see back-up)

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1 st SD splitting z_g vs ΔR



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1st SD splitting Lund Plane



If shower resolved *increased* weight of jets with smaller (groomed) mass.

White curves: lines of constant $\log(1/($

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$$(M_g/p_{T,g}))$$
 , where $M_g/p_{T,g}$

$$\frac{M_g^2}{p_{T,g}^2} \simeq z_g (1 - z_g) \Delta R^2$$

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: $\Delta R > 0.1$

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Cutting the Lund Plane







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Difference PbPb-pp of 1st SD splitting Lund plane



Removes soft & soft-collinear



Removes soft-wide

Soft-core

Extends soft-collinear region

Enhances Lund plane structure above $\Delta R > 0.1$

CMS angularity limit: $\Delta R > 0.1$



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Cutting the Lund Plane

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Groomed jet mass

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Not self-normalized:

merely reflect absence of wide angle configurations

Self-normalized:

differences due to $L_{\rm res}$ of the size of the wake effect

Soft-core

Strong discriminating power, not relying on the norm.

Comparison with (not unfolded) data



Low z_g enhancement arises in our model from smearing effects.

Strong ordering in ΔR is robust under smearing effects.

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 z_g distribution, differential in ΔR , successfully described by the Hybrid Model.

 $L_{\rm res} = \infty$ is disfavoured by data.



Comparison with (not unfolded) data



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Sensitivity to Lres



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	$\Delta R > 0.0$	$\Delta R \ < 0.1$	$\Delta R > 0.2$
PYTHIA	0.9729(2)	0.5757(7)	0.1730(4)
$L_{ m res}=0$	0.9599(8)	0.710(4)	0.092(2)
$L_{\rm res} = 2/\pi T$	0.9633(8)	0.660(3)	0.115(2)
$L_{ m res}=\infty$	0.969(1)	0.603(3)	0.161(2)

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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: good taggers for the total amount of jet activity, which regulates quenching. The smaller L_{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_g distribution, differential in ΔR . Questions power of observable to identify medium induced radiation or hard recoils.

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Correlation between n_{SD} and ΔR



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Correlation between nsp and zg



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A careful look into the selection bias





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



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Is wide configuration suppressed because formed early?

Radical test:

Assume all formation times are zero.

Small adjustment of kappa.

Almost no change in ΔR ordering.

Observable dominated by correlation between ΔR and multiplicity.





Wider jets lose more energy

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







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



Initial jet ensemble binned in energy and width

Even though each individual jet widens, final distribution is narrower



Wider jets lose more energy

 $\Delta p_\perp/p_\perp^{(\mathrm{in})}$

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"



Hybrid Model





Dijet asymmetry dominated by mass to momentum ratio, proxy for *#* vacuum splittings



Wider jets lose more energy

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







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



Larger R jets more quenched due to more energy loss sources

