Jet substructure: from proton-proton to heavy-ion collisions with ALICE

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on behalf of the ALICE Collaboration

CERN LHC Seminar
Dec 7 2021
The quark-gluon plasma

If we heat nuclear matter to $T = \mathcal{O}(100 \text{ MeV})$, thermodynamic quantities exhibit a rapid rise near a crossover temperature $T_c$. When we heat up QCD matter, deconfinement is achieved as the hadronic bound states are melted. But there are two crucial questions that must be answered if we are to understand the nature of hot QCD matter. First, what is the structure of deconfined QCD matter at certain temperatures? This of course depends on the first question – the coupling between partons. Expect the coupling in the quark-gluon plasma to become weak, since momentum transfers between partons become large and we obtain asymptotic freedom. But what is the case at ultra-high temperatures? We still need additional probes to test its microscopic structures.

### Figures

**Figure 1.4:** Lattice QCD calculation of several thermodynamic quantities including pressure $p$, energy density $\varepsilon$, entropy density $s$, and the degree of freedom $\alpha$. The quark-gluon plasma (QGP) exhibits a rapid rise in the degrees of freedom near a crossover temperature $T_c$. The phase transition is characterized by the Hadron Resonance Gas (HRG) model, which describes the quark-gluon plasma as a gas of hadrons.

**Deconfinement of quarks and gluons**

The quark-gluon plasma is a state of matter characterized by the deconfinement of quarks and gluons, allowing for the creation of a plasma-like state with a high density of energy and momentum. The diagram illustrates the transition from a hadronic phase to a quark-gluon plasma phase, highlighting the key thermodynamic quantities and their dependence on temperature.
The quark-gluon plasma

If we heat nuclear matter to \( T = \mathcal{O}(100 \text{ MeV}) \), thermodynamic quantities exhibit a rapid rise near a crossover temperature \( T_c \).

For very large \( T \), we expect this deconfined matter to be asymptotically free.
If we heat nuclear matter to $T = \mathcal{O}(100 \text{ MeV})$, thermodynamic quantities exhibit a rapid rise near a crossover temperature $T_c$.

When we heat up QCD matter, deconfinement is achieved as the hadronic bound states are melted. But there are two crucial questions that must be answered if we are to understand the mechanism of confinement. Second, what is the coupling in the quark-gluon plasma to become weak, since momentum transfers the transition? This is a particularly tantalizing question, since it may give us a view of structures, which are the relevant constituents of the system? If quasi-particles do exist, at what do they melt? And what is the structure of QCD matter during transition?

What is the coupling here?

It turns out to still be quite strong.
The quark-gluon plasma

If we heat nuclear matter to $T = \mathcal{O}(100 \text{ MeV})$, thermodynamic quantities exhibit a rapid rise near a crossover temperature $T_c$.
The quark-gluon plasma

In the last two decades it has been established that hot QCD matter is:
- Deconfined
- Strongly-coupled

But much more to learn!

Example: Bayesian extraction of specific shear viscosity ($\eta/s$)

e.g. JETSCAPE PRL 126, 242301 (2021)
The quark-gluon plasma

In the last two decades it has been established that hot QCD matter is:
- Deconfined
- Strongly-coupled

But much more to learn!

The quark-gluon plasma is a laboratory to study how complex properties emerge from the fundamental laws of quantum chromodynamics

How does this strongly-coupled fluid arise from the Lagrangian of QCD?
What are the relevant degrees of freedom of the QGP as a function of resolution scale?
How does color confinement emerge?
Heavy-ion collisions

At the LHC, we collide nuclei to produce droplets of this hot, dense state of matter known as the quark-gluon plasma

\[ T \approx 150-500 \text{ MeV} \quad t \sim \Theta \left(10 \text{ fm/c}\right) \]

The **ALICE detector** is designed for the high multiplicity environment of heavy-ion collisions

- High-precision tracking system
- Particle identification
- Forward muon arm
- Calorimetry

The ALICE detector is designed for the high multiplicity environment of heavy-ion collisions
Jet quenching in the quark-gluon plasma

The QGP is too small and short-lived to be probed by traditional scattering beams

Use jets as probes

Jets interact with the quark-gluon plasma as they traverse it:

**“Energy loss”**

\[ R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN^{\text{PbPb}}/dp_T}{dN^{\text{pp}}/dp_T} \]

The predictions typically use different strategies for each model. The model predictions, most notably between SCET predictions and the data, exhibit slight tension, particularly in the range. The shapes of the uncertainties in the data are positively correlated between different models. Neither the JEWEL nor LBT predictions include systematic uncertainties. The SCET predictions are calculated with 2\( \alpha_s \) splitting functions described above, including radiative processes.

The combined error band represents the systematic uncertainty obtained by the model predictions. The model calculations are performed according to Ref. [1].

The in-medium jet function. The predictions were performed via the exchange of “Glauber” gluons, encapsulated in jet partons with the hot QCD medium in an effective field theory (SCET), in which the jet cross section is factorized into an in-medium jet function and a “jet function” corresponding to the fragmentation of hard-scattered partons into a jet. In SCET, in cold nuclear matter was also taken into account. The plotted evolution of jet and recoiling medium particles through the 1D viscous hydrodynamics, but these differences are small relative to the values. The in-medium jet function, recoils on, 4MomSub LBT, recoils off, 4MomSub LBT, recoils on, 4MomSub LBT, recoils off.
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“Energy loss”

Substructure modification

Deflection

By modeling these interactions, we hope to determine the structure of the QGP

D. de Florian, Phys. Rev. D 79, 114014
Jet quenching in the quark-gluon plasma

Theoretical challenges in AA

- Strongly-coupled vs. weakly coupled interaction?
- Factorization in AA?
- Spacetime picture of parton shower?
- …
Jet quenching in the quark-gluon plasma

Theoretical challenges in AA
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But jet evolution is already quite complicated in pp!
- NLO, NNLO effects can be large
- Large logarithms in cross sections that contribute at all orders in $\alpha_s$
- Non-perturbative effects: hadronization, underlying event
- ...

Understanding jet quenching begins in proton-proton collisions

S. Prestel
Jet substructure

First cluster a jet, then construct an observable from its constituents

Groomed observables

- Reclass the jet constituents
- and identify a high-$Q^2$ splitting

Ungroomed observables

- Sum a quantity over all jet constituents
- e.g. jet mass: $m^2 = \left( \sum p_i \right)^2$

...
Jet substructure

Tagging

Fundamental QCD
Jet substructure

Tagging

- Boosted objects
- Quark vs. gluon jets

Fundamental QCD

Dreyer, Salam, Soyez JHEP 12 (2018) 064

James Mulligan, LBNL

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Jet substructure

**Tagging**
- Boosted objects
- Quark vs. gluon jets

**Fundamental QCD**
- Understanding validity of perturbative vs. non-perturbative physics
- Probes of quark-gluon plasma

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*Dreyer, Salam, Soyez JHEP 12 (2018) 064*
Jet substructure observables are sensitive to specific regions of QCD radiation phase space.

Each observable has:
- Fixed-order regime — $O(\alpha_s^n)$
- Resummation regime — large logarithms to all orders in $\alpha_s$
- Non-perturbative regime
Jets with ALICE

ALICE reconstructs jets at midrapidity with a high-precision tracking system (ITS+TPC) and EMCal

- $p_{T,\text{jet}} \approx 20 - 200 \text{ GeV/c}$
- $|\eta| < 0.9$

**Charged particle jets**
- High-precision spatial resolution to resolve particles
  - Excellent for jet substructure measurements

**Full jets** (charged tracks + EMCal $\pi^0, \gamma$)
- More direct comparison to theory
Jet angularities — pp

Class of IRC-safe observables:

\[ \lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha \]

\[ z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}} \]

\[ \theta_i \equiv \frac{\Delta R_{i,\text{jet}}}{R}, \quad \Delta R_{i,\text{jet}} = \sqrt{\Delta y^2 + \Delta \varphi^2} \]

Continuous parameter \( \alpha > 0 \) systematically varies weight of collinear radiation
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Continuous parameter $\alpha > 0$ systematically varies weight of collinear radiation

New measurement of jet angularities

Small $\lambda_\beta$: Non-perturbative

Larger $\lambda_\beta$: Good agreement with pQCD calculations

ALICE arXiv 2107.11303

New
Jet angularities — pp

Class of IRC-safe observables:

$$\lambda_\alpha \equiv \sum_{i \in \text{jet}} z_i \theta_i^\alpha$$

Where:

$$z_i \equiv \frac{p_{T,i}}{p_{T,\text{jet}}}$$

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Continuous parameter $\alpha > 0$ systematically varies weight of collinear radiation

Smaller $R \rightarrow$ larger non-perturbative region

Most of the distribution can be non-perturbative — can spoil agreement in perturbative region due to self-normalization

**Fig. 5:** Measurements of the jet angularities in pp collisions at $\sqrt{s} = 5.02$ TeV.

4-Figure legend:

- Data
- NLL' PYTHIA8
- NLL' Herwig7

Theory vs. Data compared for charged jets anti-$k_T$ ($R = 0.2$) $l_{\text{jet}} < 0.7, 60 < p_{T,\text{jet}} < 80$ GeV/c.

$\alpha = 1.5$

$\alpha = 2 \times (0.3)$

$\alpha = 3 \times (0.12)$

Syst. uncertainty

$\lambda_{\alpha}^{\text{NP}} = \Lambda / (p_{T,\text{jet}}^c R)$


Larkowski, Thaler, Waalewijn JHEP 11 (2014) 129
Jet angularities — pp

Non-perturbative shape function $F(k)$ to describe hadronization and underlying event effects

$$\frac{d\sigma}{d\lambda_\alpha} = \int d\sigma_{\text{parton-level}} \frac{dF(k)}{d\lambda_\alpha} \left( \lambda_\alpha - \frac{k}{p_T^{\text{jet}} R} \right) dk$$

$$F(k) = \frac{4k}{\Omega_\alpha^2} \exp \left( -\frac{2k}{\Omega_\alpha} \right)$$

Test predicted scaling of $F(k)$ with $\alpha$

$$\Omega_\alpha = \Omega / (\alpha - 1)$$

Stewart,Tackmann,Waalwijn PRL 114, 092001 (2015)
Kang, Lee, Ringer JHEP 04 (2018) 110
Kang, Lee, Liu, Ringer JHEP 10 (2018) 137
Jet angularities — pp

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Universal description of data for $\Omega < 1 \text{ GeV}$

See also: Kang, Lee, Liu, Ringer JHEP 10 (2018) 137

Stewart, Tackmann, Waalewijn PRL 114, 092001 (2015)
Kang, Lee, Ringer JHEP 04 (2018) 110
Kang, Lee, Liu, Ringer JHEP 10 (2018) 137
Jet angularities — pp

Groomed jet angularities:

\[ \lambda_{\alpha,g} \equiv \sum_{i \in \text{groomed jet}} z_i \theta_i^\alpha \]

\[ z_i \equiv \frac{p_{T,i}}{p_{T,jet}} \]

\[ \theta_i \equiv \frac{\Delta R_{i,jet}}{R} \]

Soft Drop: \( z < z_{\text{cut}} \theta^\beta \)

Dasgupta, Fregoso, Marzani, Salam 1307.00007
Larkoski, Marzani, Soyez, Thaler 1402.2657
Larkoski, Marzani, Thaler 1502.01719
Dreyer, Necib, Soyez, Thaler 1804.03657
Frye, Larkoski, Thaler, Zhou 1704.06266
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See also: CMS arXiv 2109.03340

Soft Drop grooming recovers perturbative physics

ALICE pp \( \sqrt{s} = 5.02 \) TeV
charged jets anti-\( k_T \)
\( R = 0.2 \), \( |y_{\text{jet}}| < 0.7 \)
60 < \( p_T^{\text{ch,jet}} < 80 \) GeV/c

Data

\( \lambda_{\alpha,g} = z_{\text{cut}} \lambda_{\alpha} \)

Syst. uncertainty

New

\( \lambda_{\alpha,g} \)

\( \lambda_{\alpha,g} \)

\( \alpha = 1.5 \)

\( \alpha = 2 \)

\( \alpha = 3 \)

Small \( \lambda_{\beta} \): Non-perturbative

Larger \( \lambda_{\beta} \): Good agreement with pQCD calculations

Kang, Lee, Liu, Ringer PLB 793 (2019) 41
Jet quenching in heavy-ion collisions

Theoretical challenges in AA
- Strongly-coupled vs. weakly coupled interaction?
- Factorization in AA?
- Spacetime picture of parton shower?
- ...

Jet substructure is an appealing tool to disentangle these
- Target specific regions of phase space

![Diagram of jet substructure](image_url)
Jet quenching in heavy-ion collisions

State-of-the-art jet quenching models include:

- **Modified jet fragmentation**, such as:
  - Medium-induced soft gluon radiation  
    e.g. JEWEL JHEP 03 (2013) 080
  - SCET-based factorization with modified jet function  
    e.g. Ringer et al. PRL 122 (2019) 25
  - Strongly-coupled AdS/CFT-based drag  
    e.g. Hybrid Model JHEP 09 (2015) 175
  - …

- **Expanding medium described by relativistic viscous hydrodynamics**
  - Tuned to measurements of soft observables  
    e.g. JETSCAPE PRC 103, 054904 (2021)

- **Medium response and transport**
  - Measurements include all energy flow correlated to hard jet  
    e.g. LBT PRC 91 (2015) 054908

Major advances in last decade — but large landscape of models remain to be differentiated
Heavy-ion collisions produce a large underlying event due to the hadronization of the QGP

\[ p_{T}^{\text{UE}} \approx 100 \text{ GeV}/c \text{ for } R = 0.4 \text{ jet} \]
Heavy-ion collisions: Background

Heavy-ion collisions produce a large underlying event due to the hadronization of the QGP

\[ p_T^{\text{UE}} \approx 100 \text{ GeV}/c \text{ for } R = 0.4 \text{ jet} \]

Background effects must be corrected for, in addition to detector effects

- Measurements challenging at low-\(p_T\), large-\(R\)
  
  ALICE JHEP 09 (2015) 170  
  CMS JHEP 05 (2021) 284  
  ...

- Mis-tagging of substructure objects: groomed splittings, leading subjets
  
  JM, Ploskon PRC 102 (2020) 044913
Groomed substructure — Pb-Pb

How is the hard jet substructure modified in heavy-ion collisions?

\[
z_g \equiv \frac{p_T,\text{subleading}}{p_T,\text{leading} + p_T,\text{subleading}}
\]

\[
\theta_g = \frac{\sqrt{\Delta y^2 + \Delta \phi^2}}{R}
\]

Grooming condition: \( z > z_{\text{cut}} = 0.2 \)
How is the hard jet substructure modified in heavy-ion collisions?

Grooming condition: $z > z_{\text{cut}} = 0.2$

No significant modification in $z_g$ distribution
How is the hard jet substructure modified in heavy-ion collisions?

Grooming condition: $z > z_{\text{cut}} = 0.2$

The cores of jets are narrower in Pb-Pb compared to pp collisions

Sensitive to QGP resolution length
Ungroomed jet substructure

How is the soft jet substructure modified in heavy-ion collisions?
Ungroomed jet substructure

How is the soft jet substructure modified in heavy-ion collisions?

Jet mass

$$M = \sqrt{E^2 - p_T^2 - p_z^2}$$

- 0-10% Pb–Pb $\langle p_{NN} \rangle = 2.76$ TeV
- PYTHIA Perugia 2011
- Q-PYTHIA

Poor description by jet quenching models

Large impact of medium response
Ungroomed jet substructure

How is the soft jet substructure modified in heavy-ion collisions?

Longitudinal momentum fraction of hadrons in jets

\[ D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dn_{\text{ch}}}{dz} \]

\[ z \equiv p_T \cos \Delta R / p_T^{\text{jet}} \]

Simultaneous description of high-\( z \) and low-\( z \) is an open question

See also: CMS PRC 90, 024908 (2014)
Subjet fragmentation

Cluster inclusive jets with radius $R$, then reclustering with anti-$k_T$ with radius $r$

Measure subjets to probe jet quenching
- Probe higher $z$ than hadron fragmentation measurements
- Opportunity to test universality of jet fragmentation functions

\[ z_r = \frac{p_T^{\text{ch subjet}}}{p_T^{\text{ch jet}}} \]

Parton $\rightarrow$ Subjet $\rightarrow$ Jet

Notes:
- Various measurements can be used to extract the LL splitting function, and compare to similar results.
- The large-$z$ region in inclusive subjet measurements can be used to extract the LL splitting function, and compare to similar results.
- In pp collisions, the inclusive subjet population – where in both cases the initial jet finding is done inclusively.
- In Pb–Pb collisions, we perform a philosophically similar test this universality.

In this analysis, we consider jet substructure measurements in which we first inclusively cluster jets with $k_T$ jet algorithm with jet radius $R$. In pp collisions, we perform a philosophically similar test this universality. We also choose to measure the anti-$k_T$ jet fragmentation function, which is closely related to factorization breaking. Measurement of $J_{r,\text{med}}(z)$ can then be compared to the independently extracted in-medium parton-to-subjet fragmentation function $J_{\text{med}}(z)$.

\[ J_{r,\text{med}}(z) = J_{\text{med}}(z) \]

Parton $\rightarrow$ Subjet $\rightarrow$ Jet

Results:
- Note that various measurements can be used to extract the LL splitting function, and compare to similar results.
- The large-$z$ region in inclusive subjet measurements can be used to extract the LL splitting function, and compare to similar results.
- In pp collisions, we perform a philosophically similar test this universality. We also choose to measure the anti-$k_T$ jet fragmentation function, which is closely related to factorization breaking. Measurement of $J_{r,\text{med}}(z)$ can then be compared to the independently extracted in-medium parton-to-subjet fragmentation function $J_{\text{med}}(z)$.

Subjet observables have been previously proposed as sensitive jet quenching observables. Here, we consider the fraction of transverse momentum carried by the subjet compared to the initial jet.

Inclusive subjets

- Inclusive subjet measurements can be used to extract the LL splitting function, and compare to similar results.
- The large-$z$ region in inclusive subjet measurements can be used to extract the LL splitting function, and compare to similar results.
- In pp collisions, the inclusive subjet population – where in both cases the initial jet finding is done inclusively.
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Measure subjets to probe jet quenching
- Probe higher $z$ than hadron fragmentation measurements
- Opportunity to test universality of jet fragmentation functions

\[ J_{r,\text{med}}(z) = J_{\text{med}}(z) \]

Parton $\rightarrow$ Subjet $\rightarrow$ Jet
Subjet fragmentation — Pb-Pb

Leading subjets
ISMD arXiv 2110.15467

ALICE Preliminary
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
Charged jets anti-\( k_T \) subjets
\( R = 0.4 \), \( |\eta_{\text{jet}}| < 0.5 \)
\( 80 < p_T, \text{ch jet} < 120 \text{ GeV/c} \)
anti-\( k_T \) subjets \( r = 0.1 \)

Hardening distribution at intermediate \( z_r \)
- Large quark-gluon differences in vacuum
- Competing effects
  - Gluon suppression \( \rightarrow \) larger \( z_r \)
  - Soft radiation \( \rightarrow \) smaller \( z_r \)

Well-described by theoretical predictions
- Consistent with universality of jet fragmentation in QGP

Neill, Ringer, Sato JHEP 07 (2021) 041

Qiu, Ringer, Sato, Zurita PRL 122 (2019) 25
Subjet fragmentation — Pb-Pb

**Leading subjets**

*ISMD arXiv 2110.15467*

- ALICE Preliminary
  - $\sqrt{s_{NN}} = 5.02$ TeV
  - Charged jets: anti-$k_T$ $R = 0.4$, $|\eta_j| < 0.5$
  - $80 < p_T, \text{ch jet} < 120$ GeV/c
  - anti-$k_T$ subjets: $r = 0.1$

**Hint of suppression as $z_r \to 1$**

- At $z_r \to 1$, the sample becomes closer to purely quark jets!
- Expose region depleted by soft medium induced emissions

**New path to disentangle quenching effects**
Outlook — jet substructure in heavy-ion collisions

By measuring carefully chosen observables...

□ Calculable in proton-proton collisions
□ Corrected for background and detector effects

...we are producing an emerging picture of jet quenching phenomenology

□ Hard splitting momentum distribution not strongly modified — $z_g$
□ Collimation/filtering of wide jets — $\theta_g$
□ Medium-induced soft splitting can be exposed in region dominated by quark jets — $z_r$
Where do we go from here?

Bayesian inference to extract QGP properties using multiple jet observables

- Controlled comparisons of specific aspects within model (q vs. g, medium response, …)

Observable design to add new information to these global extractions

- Model sensitivity

- Information content distinguishing pp from AA jets

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ALICE measurements of jet substructure in proton-proton collisions are providing new tests of our first-principles understanding of QCD

- Explore the transition from the perturbative to non-perturbative regimes
- More results not shown here: dead cone, Lund plane, axis differences, Dynamical grooming, …

New measurements of jet substructure in heavy-ion collisions are producing an emerging picture of jet quenching and starting to connect to QGP properties

- Emphasis on observables that can be directly compared to theoretical calculations

ALICE jet capabilities in LHC Runs 3+4 will enable new extractions of QGP properties

- Increased statistics by 50-100x, improved tracking — HF-jet, $\gamma$-jet, larger $p_T$