Exploring Hot-QCD Matter Properties with Jets

Joern Putschke
Recall: Water
Phase diagram of QCD Matter

- **nucleus**
- **Heat**
- **Compress**
- **QGP**
- **nucleon boundary irrelevant**
Phase diagram of QCD Matter

Quark Gluon Plasma:
A state of matter without color confinement that exhibits collective effects

Vacuum

Nuclear Matter

QGP

Critical Point

Color Superconductivity

Color Flavor Locking Phase

Hadron Gas

Early Universe

Crossover

More on this part of the phase diagram see talk by D. Cortina

CHEN06

KSTD02
Basic Idea: Smash heavy nuclei at highest possible energy ⇒ create conditions (hot and dense) sufficient to “melt” matter into a QGP (the state of all matter ~6 µs after the Big Bang)
In a nutshell: The QGP at RHIC and the LHC

At RHIC and the LHC we see the **hottest**
**densest**
**matter ever studied**
in the laboratory that
**flows**
as a (nearly) **perfect fluid**
with systematic patterns consistent with
**quark (partonic) degrees of freedom**
and a viscosity to entropy density ratio **lower**
than any other known fluid
and it is
**opaque to colored objects**

**High-\(p_T\) suppression/“Jet-Quenching”** → Focus of this talk!

- **\(T=200-400\text{ MeV} \sim 3.5 \cdot 10^{12} \text{ K}\)**
  - **Remark:** Center of the sun \(\sim 10^7\text{K}\)

- **\(\varepsilon=30-60\varepsilon_{\text{nuclear matter}}\)** (well above \(\varepsilon_c\))
  - **Remark:** With such an energy density, the yearly energy output of the US would fit in a box of 5\(\mu\text{m}\)!

- **large elliptic/anisotropic flow (\(v_n\))**

- **valence quark scaling**

More on this in C. Shen and A. Ohlson talks later this week!
How can we look for more (microscopic) details?

**Back in time: The Rutherford Experiment**

*Ernest Rutherford*
How can we look for more (microscopic) details? “Tomography” of the QGP

Detector

Calibrated
“LASER/x-ray”
How can we look for more (microscopic) details? “Tomography” of the QGP

Detector

Calibrated “LASER/x-ray”

Human body
How can we look for more (microscopic) details? “Tomography” of the QGP

Calibrated
“LASER/x-ray”
Unfortunately not possible!
Lifetime of QGP way to short :-(
How can we look for more (microscopic) details? “Tomography” of the QGP

Self-generated “hard” probes in the very early stages of HI collisions

‘Hard’ processes/probes have a large scale in the calculation that makes perturbative QCD applicable:

• **high** momentum transfer, $Q^2$
• **high** transverse momentum, $p_T$
• **high** mass, $m$ (Heavy flavor HI parallel sessions!)
Before we can utilize hard probes/jets (and their modifications/tomography) to probe the medium in heavy-ion collisions we first have to establish that:

1) **The probe is calibrated:**
   Comparison of pQCD calculations with p-p measurements

2) **Control experiment:**
   Measure initial state/Cold Nuclear Matter (CNM) effects; 
   Probe the “cold medium” via p-Pb (d-Au) collisions (compare to p-p)

* Indications of collective effects observed in small systems (p-p and p-Pb); QGP formation!? More on this in A. Ohlson’s talk!
Jets = “Seeing” quarks and gluons (partons)

In high-energy collisions, observe the fragments of quarks, gluons (‘jets’)  
Jet Clustering: Energy sum of all the fragments = jet energy = parton energy!
“Seeing” jets in HI collisions ...

well, at least some are clearly visible!

Need to correct for the underlying heavy-ion background!
“Seeing” jets in HI collisions ...

well, at least *some* are clearly visible!

Need to correct for the *underlying* heavy-ion background!

This is a non-trivial task, *but* we developed the necessary experimental corrections and *established* jet measurements as a well *controlled* tool in heavy-ion collisions!
The QGP at the LHC

• fireball hotter (~20%) and denser (~x2) and longer lifetime wrt RHIC

• bulk dynamics, $v_n(p_T)$, similar at RHIC and LHC, mainly driven by initial state “geometry”

See C. Shen and A. Ohlson

Huge increase in yield of hard probes/jet production!
The QGP at the LHC

- fireball hotter (~20%) and denser (~x2) and longer lifetime wrt RHIC
- bulk dynamics, $v_n(p_T)$, similar at RHIC and LHC, mainly driven by initial state “geometry”

Mainly gluon jets ($p_T<200$ GeV) at the LHC. Quark jets at RHIC $p_T>40$ GeV.

Huge increase in yield of hard probes/jet production!

Pythia p+p

- LHC: $\sqrt{s} = 5.5$ TeV
- RHIC: $\sqrt{s} = 0.2$ TeV

Anti-$k_T$ R=0.4
**Naive: What is jet quenching?**

Jet quenching = Gluon radiation:
Multiple final-state gluon radiation off the produced hard (colored) parton induced by interactions with the hot and dense colored medium ~ “Gluon Bremsstrahlung”

Jet in vacuum

\[ E_{\text{Vacuum}} \]

\[ \rightarrow \lambda \]

\[ \uparrow q_{T} \sim \mu \]

\[ \omega = xE \]

\[ \omega = (1-x)E \]
Naïve: What is jet quenching?

Jet quenching = Gluon radiation:
Multiple final-state gluon radiation off the produced hard (colored) parton induced by interactions with the hot and dense colored medium ~ “Gluon Bremsstrahlung”

→ Modification of the Jet Structure/Fragmentation Function
(fractional jet momentum carried by the individual jet particles/constituents)

Jet in vacuum

Jet in medium

Jet quenching/glue radiation in QGP depends on:
path-length, density, parton energy, virtuality
(resolution scale) and light-quarks vs gluon vs heavy-quarks
(gluons should lose more and heavy quarks less energy)

Jet broadening

Suppression of high-p\(_T\) particles

Enhancement of low-p\(_T\) particles

\[ E_{\text{Jet in medium}} = E_{\text{Jet in vacuum}} \]
The Nuclear Modification Factor $R_{AA}$ at RHIC and LHC

$$R_{AA} = \frac{dN^{AA}/dp_t}{\langle N_{coll}\rangle dN^{pp}/dp_t}$$

Expectation for hard (pQCD) processes:

$R_{AA}=1 \leftrightarrow N_{coll}$ scaling $\leftrightarrow$ no QGP effects

(1) Direct (colorless) photons and W/Z are not suppressed ✓
### The Nuclear Modification Factor $R_{AA}$ at RHIC and LHC

The nuclear modification factor $R_{AA}$ is defined as:

$$R_{AA} = \frac{dN_{AA}/dp_t}{\langle N_{coll} \rangle dN_{pp}/dp_t}$$

**Expectation for hard (pQCD) processes:**

$R_{AA} = 1 \Leftrightarrow N_{coll}$ scaling $\Leftrightarrow$ no QGP effects

**Results from various experiments:***

- **PHENIX Au+Au, $S_{NN} = 200$ GeV, 0-10% most central**
  - PHENIX (Adare et al., 2007a, 2008c, 2012a, 2013d, 2015b)
  - PHENIX (Adare et al., 2010c)
  - PHENIX (Adare et al., 2013a, 2013e)
  - PHENIX (Adare et al., 2012b)

- **CMS *PRELIMINARY* PbPb $\sqrt{s_{NN}} = 2.76$ TeV $\int L dt = 7-150$ fb$^{-1}$**
  - CMS (Khachatryan et al., 2016b)
  - CMS (Khachatryan et al., 2016a)
  - CMS (Khachatryan et al., 2017a)

- **Other results:**
  - RHIC (Adams et al., 2003a, 2005a)
  - RHIC (Adams et al., 2004a, 2005a)
  - RHIC (Adams et al., 2006a)
  - RHIC (Adams et al., 2007a, 2008a, 2010b, 2011a)
  - RHIC (Adams et al., 2012a, 2013b)

(I) **Direct (colorless) photons and W/Z are not suppressed** ✓

(II) **Hadrons (colored) are suppressed in central heavy-ion collisions by a (huge) factor of 5 (decreasing with $p_T$ at the LHC)** ✓

→ Suppression of high-$p_T$ particles

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Joern Putschke (WSU), INCP 2019, Glasgow
The Nuclear Modification Factor $R_{AA}$ at RHIC and LHC

$$R_{AA} = \frac{dN^{AA}/dp_t}{\langle N_{coll}\rangle dN^{pp}/dp_t}$$

ATLAS, PLB 790 (2019) 108

ATLAS anti-$k_t$ $R = 0.4$ jets, $\sqrt{s_{NN}} = 5.02$ TeV

2015 data: Pb+Pb 0.49 nb$^{-1}$, pp 25 pb$^{-1}$

$\langle T_{AA} \rangle$ and luminosity uncer.

| $|y| < 2.8$ |
|----------------|
| 0 - 10% |
| 20 - 30% |
| 40 - 50% |
| 60 - 70% |

Expectation for hard (pQCD) processes:

$R_{AA}=1 \iff N_{coll}$ scaling $\iff$ no QGP effects

(I) Direct (colorless) photons and W/Z are not suppressed $\checkmark$

(II) Hadrons (colored) are suppressed in central heavy-ion collisions by a (huge) factor of 5 (decreasing with $p_T$ at the LHC) $\checkmark$

$\rightarrow$ Suppression of high-$p_T$ particles

(III) Inclusive jet production in central heavy-ion collisions is suppressed for small $R=0.4$ jets (up to $\sim 1$ TeV!) $\rightarrow$ Jet Broadening $\checkmark$
An other way to look at it: Di-Jet Imbalance ($A_J$) at the LHC

$$A_J = \frac{p_T^{\text{Lead}} - p_T^{\text{SubLead}}}{p_T^{\text{Lead}} + p_T^{\text{SubLead}}}$$
An other way to look at it: Di-Jet Imbalance ($A_J$) at the LHC

Significant di-jet momentum imbalance $A_J$ observed in central Pb+Pb

Less modification in non-central Pb+Pb as expected from smaller QGP medium
(Biased) Di-Jet Imbalance ($A_J$) at RHIC

STAR, PRL 119, 062391 (2017)

With $p_T^{\text{Cut}} > 2$ GeV/c:
- $p+p$ HT $\oplus$ Au+Au MB
- Au+Au HT

$p_T^{\text{Cut}}>0.2$ GeV/c, Matched:
- $p+p$ HT $\oplus$ Au+Au MB
- Au+Au HT

Au+Au, 0-20%
Anti-$k_T$, $R=0.4$

With $p_T^{\text{Cut}} >2$ GeV/c:
- $p_T^{\text{lead}} > 20$ GeV/c
- $p_T^{\text{sublead}} > 10$ GeV/c

Biased (hard-core) selected Jet production vertex

"Jet Geometry Engineering" via constituent $p_T$ cut

Unbiased Jet production vertex

Joern Putschke (WSU), INCP 2019, Glasgow
(Biased) Di-Jet Imbalance ($A_J$) at RHIC

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Select modified di-jet pairs with hard-core bias in Au+Au

→ Quenched jet energy is recovered at low $p_T$ within a cone of $R=0.4$ (also jet broadening in 0.2 – 0.4 observed)

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STAR, PRL 119, 062391 (2017)

Unbiased Jet production vertex

Biased (hard-core) selected Jet production vertex

“Jet Geometry Engineering” via constituent $p_T$ cut

Select $p_T^\text{cut} > 2 \text{ GeV/c}$:
- p+p HT + Au+Au MB
- Au+Au HT

$p_T^\text{cut} > 0.2 \text{ GeV/c, Matched:}$
- p+p HT + Au+Au MB
- Au+Au HT

Au+Au, 0-20%
Anti-$k_T$, $R=0.4$

With $p_T^\text{cut} > 2 \text{ GeV/c}:
- p_T^\text{lead} > 20 \text{ GeV/c}
- p_T^\text{sublead} > 10 \text{ GeV/c}$

Nick Elsey, STAR - Hard Probes 2018, France

Joern Putschke (WSU), INCP 2019, Glasgow
Jet Evolution/Parton Shower in the QGP

In vacuum: perturbative QCD, Jet Evolution/Parton Shower is angular/virtuality ordered

\[ Q_0^2 >> Q_1^2 >> Q_2^2 >> \ldots \rightarrow \text{two fundamental scales momentum and angle/virtuality} \]

Strong coupling, AdS-CFT (String Theory)?

Energy Thermalization

Hadronization

(Initial) Virtuality \( Q_0^2 \)

(AP) Splitting Function

\( t_f \approx \omega/k_T^2 \approx 1/(\omega \Delta R^2) \)

Quark Gluon Plasma

QGP temperature and density decreasing

Time

Vacuum

Detector

Jet 0: pt: 70.0 GeV

Jet 1: pt: 70.0 GeV

Meson

Baryon
Jet Evolution/Parton Shower in the QGP

In vacuum: perturbative QCD, Jet Evolution/Parton Shower is angular/virtuality ordered.

\[ Q_0^2 >> Q_1^2 >> Q_2^2 >> \cdots \rightarrow \text{two fundamental scales momentum and angle/virtuality} \]

Energy Thermalization

*(Initial) Virtuality \( Q_0^2 \)

(AP) Splitting Function

Splitting angle

\[ t_f \approx \frac{\omega}{k_T^2} \approx \frac{1}{(\omega \Delta R^2)} \]

Strong coupling, AdS-CFT (String Theory)?

Quark Gluon Plasma

Hadronization

Energy loss depends on the virtuality (evolution)

For example: A. Majumder and JP, PRC93 (2016) no.5, 054909

QGP temperature and density decreasing

Time

Vacuum

Jet 0. pt: 70.0 GeV

Jet 1. pt: 70.0 GeV

Detector
Jet Evolution/Parton Shower in the QGP

In vacuum: perturbative QCD, Jet Evolution/Parton Shower is angular/virtuality ordered

\[ Q_0^2 >> Q_1^2 >> Q_2^2 >> \cdots \]

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Energy Thermalization

Time

QGP temperature and density decreasing

Energy loss depends on the virtuality (evolution)

For example: A. Majumder and JP, PRC93 (2016) no.5, 054909

Medium modified Splitting function

For example: SCET: arXiv:1608.07283
Jet Evolution/Parton Shower in the QGP

In vacuum: perturbative QCD, Jet Evolution/Parton Shower is angular/virtuality ordered

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In vacuum: perturbative QCD, Jet Evolution/Parton Shower is angular/virtuality ordered

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Strong coupling, AdS-CFT (String Theory)?

Energy Thermalization

Hadronization

(Initial)
Virtuality
$$Q_0^2$$

(AP) Splitting Function

Splitting angle

Quark Gluon Plasma

Time

QGP temperature and density decreasing

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Medium modified Splitting function

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Medium modified Splitting function

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Color (De)Coherence:
Medium resolves the parton splitting

$$\theta > \theta_c \sim \left(\hat{q}L^3\right)^{-1/3}$$

For example: Casalderrey-Solana, Methar-Tani, Salgado, Tywoniuk: PLB 725 (2013) 357
Access fundamental Quantities via Jet-Substructure Observables

<table>
<thead>
<tr>
<th>Fragmentation Functions</th>
<th>Classic Jet Shapes</th>
<th>Groomed Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single hadron</td>
<td>All hadrons</td>
<td>Subset of hadrons</td>
</tr>
</tbody>
</table>

**fragmentation function**

\[ D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}} \]

**differential jet shape**

\[ \rho(r) = \frac{1}{p_{\perp}^{\text{jet}}} \sum_{k \text{ with } \Delta R_{k,J} \in [r, r+\delta r]} p_{\perp}^{(k)} \]

**girth = broadening**

\[ g = \frac{1}{p_{\perp}^{\text{jet}}} \sum_{k \in J} p_{\perp}^{(k)} \Delta R_{k,J} \]

**jet mass, groomed & ungroomed**

\[ m^2 = \left( \sum_{i \in \text{(sub)jet}} p_{i,\perp}^2 \right)^2 \]

**\( z_g, \Delta R_{12} \)**

\[ z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left( \frac{\Delta R_{1,2}}{R_J} \right)^\beta \]

For SoftDrop see Ladorzki et al JHEP 1405 (2014) 146

Joern Putschke (WSU), INCP 2019, Glasgow
Access fundamental Quantities via Jet-Substructure Observables

Fragmentation Functions

Classic Jet Shapes

Groomed Observables

Single hadron

All hadrons

Subset of hadrons

**fragmentation function**

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D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}
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**differential jet shape**

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\rho(r) = \frac{1}{p_{\perp,\text{jet}}} \sum_{k \text{ with } \Delta R_{k,J} \in [r,r+\delta r]} p_{\perp}^{(k)},
\]

**girth \equiv broadening**

\[
g = \frac{1}{p_{\perp,\text{jet}}} \sum_{k \in J} p_{\perp}^{(k)} \Delta R_{k,J},
\]

**jet mass, groomed & ungroomed**

\[
m^2 = \left( \sum_{i \in \text{(sub)jet}} p_i^\mu \right)^2
\]

**\(z_g, \Delta R_{12}\)**

\[
z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}}
\]

Jet Mass ~ \(z\theta^2\) ~ Virtuality

\(z_g\) ~ Splitting Function

\(\Delta R_{12}\) ~ opening angle (of the hardest split)
Modification of the Splitting Function in Pb-Pb collisions

Jets with two hard subjets (large $z_g$) “relatively” more suppressed $\rightarrow$ strong constraints on theory!

$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$
Jet Mass Measurements in Pb-Pb at the LHC

Experimental access to virtuality via jet mass measurements

→ Access to both relevant pQCD quantities: Energy and Virtuality!

Indication of slightly reduced jet mass/lower virtuality in PbPb collisions for lower energetic jets < 100 GeV/c
Jet Mass Measurements in Pb-Pb at the LHC

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Indication of slightly reduced jet mass/lower virtuality in PbPb collisions for lower energetic jets < 100 GeV/c

Cancelling effects from medium modifications of the shower and medium response?
Jet-Substructure observables allow access to both relevant pQCD quantities: Energy and Angle/Virtuality (Evolution) → providing stringent constraints on partonic energy loss theory

The jet opening angle and virtuality is related to a Resolution scale at which the jet probes the medium → exploring the microscopic nature of the QGP at various scales
Key Idea: Use jet-substructure as a selection tool

- Identify an observable sensitive to the jet’s inherent angular/virtuality scale
- Measure jet energy loss differentially in the angular/virtuality scale (and momentum)
No significant modification of jet $R_{AA}$ vs $m/p_T$ observed*

Cancelling effects(?): Medium recoil *increases* jet mass vs jet broadening outside jet cone *reduces* the jet mass

*Remark: $m/p_T$ experimentally *easier* (smaller sys. uncertainties) but mixes momentum and virtuality (not an issue in pp), better $R_{AA}$ vs jet mass
Splitting Function ($z_g$) vs $R_g$ at the LHC

Suppression of $z_g$ at large opening angles
Indication of enhancement at low opening angles

Qualitative agreement with the expectation from Color (De)Coherence picture.

**BUT:** Models w/o color coherence consistent with data → other mechanisms: for example interplay between formation time and medium length …
(Biased) Di-Jet ($A_J$) vs (R=0.1) Sub-jet Angle at RHIC

**Key Idea**

Use jet-substructure as a selection tool

- Identify an observable sensitive to the jet’s inherent angular scale
- Measure jet energy loss differentially in the angular scale

**Selected Observables**

- Cluster all jet constituents into anti-$k_t$ jets of smaller radius (0.1)
- Choose the leading and subleading SubJets

\[ \frac{z_{SJ}}{u_1D703SJ} = \frac{\Delta R (\text{Blue Axis}, \text{Red Axis})}{\text{Blue } p_T / (\text{Blue } p_T + \text{Red } p_T)} \]


**Quenched jet energy is recovered at low $p_T$ within R=0.4 for all $\theta_{SJ}$**

Jet Geometry Engineering/surface bias, (hardest) split most likely outside the medium (formation time) and resulting modification is due to soft gluon radiation from a single color charge.
The path forward ...
The JETSCAPE Effort

A. Majumder, Hard Probes '15

Theoretical and experimental physicists, computer scientists, statisticians

- **Multi-Stage Energy Loss:**
  Apply theoretical description in their respective (kinematic) range of validity

- **Mission Statement:** Extensive, extensible event generator

- **Note:** Framework is agnostic to “multi-stage”, ”energy loss”

- Includes an advanced/Bayesian Statistical analysis tool

www.github.com/JETSCAPE/JETSCAPE
RHIC and LHC complementary provide stringent constraints on jet energy loss calculations (new dedicated “jet detector” sPHENIX at RHIC in 2023)

Jets (via substructure observables) probe the QGP over a wide range of length scales → Jets are QGP microscopes → measure the (fundamental) microscopic nature/quasi-particle nature of the QGP at RHIC and the LHC
Exciting times and future prospects for hard probes in heavy-ion physics!

We have all the tools and equipment ...

Heavy-flavor and Quarkonia

Direct photons
W/Z, top ...

Jets and Jet Substructure

New theoretical approaches and quantitative improvements