Jet quenching in heavy-ion collisions at the LHC

Marta Verweij
CERN

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Thousands of particles are produced in one heavy ion collision.
Heavy ion collision

Lorentz-contracted nuclei approach

Nuclei collide. Binary collisions between quarks and gluons can produce jets or heavy quarks

Quarks and gluons freed, plasma formed

Plasma expands and cools, quarks and gluons form bound states (particles)
Big bang

The ‘same’ quark-gluon soup as is created in a heavy ion collision
In heavy ion collisions a stiff liquid of quarks and gluons is formed

Just like a fraction of a second after the big bang

What we want to learn about this state of matter
- Viscosity
- Transport coefficients
- How it evolves with time
- How it dissipates at the end
- …

Partons from hard scattering are an experimental tool to study the properties of the medium
Viscosity

Viscosity is minimal at liquid to gas transition

For a gas:
viscosity increases with T

For a liquid:
viscosity decreases with T

QGP viscosity is lower than any type of atomic matter

QGP = quark gluon plasma

How do we measure this?
Hard probes in QCD matter

Heavy-ion collisions produce dense QCD matter
→ dominated by soft partons
\( p_T \sim 100\text{-}300\ \text{MeV} \)

Hard scatterings produce high energy partons

- Initial state production known from pQCD
- Parton loses energy due to interaction with medium
  → medium induced gluon radiation

Use hard partons to explore QCD matter
Jet production in medium

The theorist perspective*

Parton interacts with colored medium → additional gluon radiation
Phenomenon known as Jet Quenching

* according to an experimentalist (me)
Jet production in medium

The experimentalist perspective*

* according to an experimentalist (me)
Find the jets

Jets are not so easy to find in a heavy-ion collision
Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)
Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)

Jet energy asymmetry

\[ A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}} \]

PRL 105 (2010) 252303
Dijets in PbPb

First direct observation of jet quenching (Dec. 2010 LHC)

\[ A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}} \]

Dijets in PbPb are less balanced in energy
Jets in heavy-ion collisions

- Due to interactions of the hard parton with the medium, the jet is modified relative to pp: Jet Quenching

\[ R_{AA} = \frac{\sigma^{inel}_{pp}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}}{dp_T d\eta} \frac{d^2 \sigma_{pp}}{dp_T d\eta} \]

Experimental challenge in HI collisions:
Separate jet signal from large soft background originating from bulk
Schematic picture of energy loss mechanism in hot dense matter

- Energy loss due to gluon bremsstrahlung in a hot dense medium

\[ x_E = (1-x)E \]

\[ \Delta E = xE \]
Outgoing quark spectrum
Same temperature

Energy fraction of quark after leaving the medium. Fixed length, fixed temperature for all models

- $x_E = 1 - \Delta E/E$
- $x_E = 0$: Absorbed quarks
- $x_E = 1$: No energy loss

For fixed temperature:
- $<\text{Ngluons}>$ larger for opacity expansion than multiple soft scattering approximation
- Suppression: AMY > DGLV > ASW-MS

Nuclear modification factor $R_{AA}$

Nuclear modification is measured by taking ratio between measured yield PbPb and pp collisions.

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

- 'Energy loss'
- 'Absorption'
- Downward shift

Shift spectrum to left

Marta Verweij
Centrality in HI collisions

Medium density increases with centrality

Peripheral collisions

Central collisions

Nuclear modification factor $R_{AA}$

Nuclear modification is measured by taking ratio between measured yield PbPb and pp collisions

$$R_{AA} = \frac{\sigma_{pp}^{inel} \frac{d^{2}N_{AA}}{dp_{T}d\eta}}{\langle N_{coll} \rangle \frac{d^{2}\sigma_{pp}}{dp_{T}d\eta}}$$

High $p_{T}$ hadron production is suppressed by a factor 2-6

Large amount of energy is lost

Can we recover this energy by reconstructed jets?
Heavy flavor
Dead cone effect

Radiated wave cannot escape quark

$\beta < 1$ for heavy quarks
$\Rightarrow$ Minimum angle for radiation

$\sin \theta_{DC} = 1 - \beta^2 = \left(\frac{M}{E}\right)^2$
D mesons

Heavy flavor: testing flavor dependence of jet quenching

Dead cone effect due to mass of charm
Light vs ‘Heavy’

Light and heavy hadrons equally suppressed

Mass of charm not heavy enough to show dead cone effect

Expecting B meson from run 2 data
Suppression is similar for hadrons (leading fragments) and jets
Suppression vs centrality

Jets are less suppressed in QGP temperature is lower

\[ \rightarrow \text{Amount of jet quenching varies with medium temperature} \]
Jet shapes and structures

Jet shape observables: energy distribution within a jet
Sensitive to dynamics of parton shower

Radial profile
Transverse fragment distribution
Energy

'Fragmentation function'
Longitudinal fragment distribution
Multiplicity

Small enhancement at large $R$ and small $z$: 1-2 GeV + 2 particles
+ suppression at intermediate $R$ and $z$
Jet shape at large angle

Missing energy from jet is recovered at very large distance from jet
Jet superstructure and global event shapes

The effects of jet quenching persist up to large angles.
The global event shape is modified and not only inner-jet properties.

Color vs colorless probes

Additional gluon radiation of partons due to presence of medium is known as Jet Quenching

quarks will always quench with medium  
→ Measured $p_T$ of b-jet lower than in pp ($R_{AA} < 1$)
→ Photons, Z and $W(\rightarrow l\nu)$ not quenched ($R_{AA} = 1$)
γ-jet correlation

Advantage of photon-jet correlations:
Photon isn’t affected by medium presence
→ You know the kinematics of the system

Experimental observable: ratio between jet $p_T$ and photon $p_T$

$$x_{J\gamma} = \frac{p_T^{\text{jet}}}{p_T^\gamma}$$
Z-jet

Colorless probes don’t interact with hot dense medium
Z-jet ideal probes to study what happens with the recoiling quark parton shower
Experimentally cleaner than $\gamma$-jet

But low cross section
→ Becoming available in LHC run2
Data vs Theory

Multiple models describing the same physics → Suppression of charged hadrons
Data vs Theory

Extracting transport coefficient from data

\[ \frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2, & \text{at RHIC,} \\ 3.7 \pm 1.4, & \text{at LHC,} \end{cases} \]

\[ \hat{q} \approx \begin{cases} 1.2 \pm 0.3, & \text{GeV}^2/\text{fm} \text{ at } T = 370 \text{ MeV,} \\ 1.9 \pm 0.7, & \text{at } T = 470 \text{ MeV,} \end{cases} \]

\[ \frac{\hat{q}}{T^3} \propto \left( \frac{\eta}{s} \right)^{-1} \]

\[ \frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}} \]

for a QCD medium

JET Collaboration, PRC 90, 014909 (2014)
A new idea
for run2 + future colliders:

top quarks in the QGP

never observed before
Top in heavy ion collisions
Why?

To study the properties of the color-charged quark-gluon plasma (QGP) created in heavy-ion collisions

Top decays before thermalization of medium
Top in heavy ion collisions

Why?

To study the properties of the color-charged quark-gluon plasma (QGP) created in heavy-ion collisions

Top decays before thermalization of medium

→ Probes the early stages of the medium

Color-charged decay products of top interact with medium

Quarks and gluons do interact with medium → additional gluon radiation wrt vacuum (pp)

W, l, v do not interact with medium
Jet quenching

Additional gluon radiation of partons due to presence of medium is known as Jet Quenching

Quarks will always quench with medium 
→ Measured $p_T$ of b-jet lower than in pp

$W \rightarrow q\bar{q}$ becomes interesting. 
Do not expect to recover W mass

Quarks from W decay propagate through medium 
→ quenching
Time evolution of QGP

Decay time of top larger if $p_T$ is larger
Scan of top kinematics allows to study the time evolution

Lifetimes
Top: 0.15 fm/c
W: 0.1 fm/c
QGP formation time: $\sim$0.6 fm/c

Heavy ions at FCC meeting
Liliana Apolinario

Becomes mainly relevant at FCC
Top in QGP

Formation time of QGP

Delta E_1 > Delta E_2

Top and W don’t decay immediately
Boosted Tops

Due to color coherence the effect of medium-induced radiation is expected to be delayed in time. Top allows to study these (de)coherence phenomena.

Top and W don’t decay immediately. Allows to study time evolution of medium. Top allows to study these (de)coherence phenomena.
### Expected t-tbar & single-top yields

- **Final-state:** \( \text{ttbar} \rightarrow b\bar{b} + 2\ell \ (e,\mu) + \text{MET}(2\nu) \)
- **Final-state:** single \( t \rightarrow b + 1\ell \ (e,\mu) + \text{MET}(\nu) \)

<table>
<thead>
<tr>
<th>System</th>
<th>(\sqrt{s_{\text{NN}}}) (TeV)</th>
<th>(L_{\text{int}})</th>
<th>(N(\text{t-tbar}))</th>
<th>(N(\text{single-t}))</th>
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<tr>
<td>Pb-Pb</td>
<td>5.5</td>
<td>1 nb(^{-1})</td>
<td>57</td>
<td>73</td>
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<td></td>
<td></td>
<td>10 nb(^{-1})</td>
<td>566</td>
<td>730</td>
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<td>p-Pb</td>
<td>8.8</td>
<td>0.2 pb(^{-1})</td>
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<td>185</td>
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<td></td>
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<td>1 pb(^{-1})</td>
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<td>930</td>
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<tr>
<td>Pb-Pb</td>
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<td>5 nb(^{-1})</td>
<td>31.500</td>
<td>16.900</td>
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<tr>
<td>p-Pb</td>
<td>63</td>
<td>1 pb(^{-1})</td>
<td>66.650</td>
<td>31.900</td>
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- **LHC (nominal \(L_{\text{int}}\)):** 50-200 t-tbar pairs & single-t in Pb-Pb, p-Pb
- **O(10^3) tops for enhanced lumis.**

- **FCC:** \((15-60) \times 10^3\) t-tbar pairs & single-t in Pb-Pb, p-Pb
**Expected t-tbar & single-top yields**

- Final-state: $t\bar{t} \rightarrow b\bar{b} + 2\ell (e,\mu) + \text{MET}(2\nu)$
- Final-state: $t \rightarrow b + 1\ell (e,\mu) + \text{MET}(\nu)$

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<tr>
<td>LHC (nominal)</td>
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<tr>
<td>FCC: (15-60)</td>
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CMS collected 0.5 nb$^{-1}$ in December
Expect $\sim$25 $t\bar{t}$ in fully leptonic channel
And still at least 1 PbPb period during run2
Summary

Overwhelming evidence that parton shower in heavy ion collisions is modified

Why do we keep adding measurements?
Each measurement is sensitive to different aspect of energy loss

Working towards consisting of the most nearly perfect liquid
backup
Perfect liquid

RHIC Scientists Serve Up 'Perfect' Liquid
New state of matter more remarkable than predicted — raising many new questions

April 18, 2005

The 4 experiments at RHIC (BNL) saw a quark-gluon liquid of very low viscosity

Time evolution

- Parton travels through evolving medium
- Parton sees different medium at each step in space and time
- Density of medium decreases as function of space and time
Effects of the boost

Liliana Apolinario, Carlos Salgado
Heavy Ions at FCC meeting