Time evolution of a medium-modified jet

Liliana Apolinário

Special thanks to:
Ruben Conceição, Guilherme Milhano and Jesse Thaler
QGP: An Evolving Medium

- Space-time evolution of the Quark-Gluon Plasma (LHC)
- Fast evolving and extended medium:
  - Initial time: $\tau_0 < 1 \text{ fm/c}$
  - QGP lifetime: $\tau \sim 10 \text{ fm/c}$
- Strong time-dependence of the medium properties (expansion and cooling of the system)
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- QGP Probes
  - Integrated result of the whole medium evolution

Flow coefficients, Hadrochemistry (soft probes),…
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⇒ Need strategies to probe the time-structure of the QGP!

Jets, Quarkonia (hard probes),…
Time probing of the QGP

- Recent strategies to probe space-time evolution of the QGP:

  **Time-delayed probes**
  (boosted tops)

  **Initial time probes**
  (High pt harmonics)
Time probing of the QGP

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High-\(p_T\) Harmonics

- A description of high-\(p_T\) anisotropic flow needs both hard and soft sectors:

- Framework to change quenching during early stages (based on quenching weights)

Potential to constrain the dynamics of the initial stages of the evolution

Switching off quenching during the first 0.6 fm/c

[Andrés et al (19)]
Time probing of the QGP

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- Recent strategies to probe space-time evolution of the QGP:
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Boosted Tops: time delayed probe

- Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times

![Graph showing total delay time and standard deviation as a function of transverse momentum with stacked bands for different components: coherence, W decay, and top decay times.](image)

**Graph Details:**
- **Legend:**
  - Total delay time and std. dev ($\tilde{q} = 4 \text{ GeV}^2 \text{ fm}^{-1}$)
  - Coherence Time
  - W decay Time
  - Top decay Time
- **Axes:**
  - X-axis: $p_{t,\text{top}}^{\text{reco}}$ (GeV)
  - Y-axis: $\langle t_{\text{tot}} \rangle$ (fm/c)
- **Annotations:**
  - Equation (1)
  - CMS gives a projection for the uncertainties on the impact of standard quenching for the purpose of producing Fig. 5.
- **Equation:**
  \[ \langle t_{\text{tot}} \rangle = \langle t_{\text{coh}} + t_{\text{W decay}} + t_{\text{Top decay}} \rangle \]
- **Additional Notes:**
  - Aside from luminosity considerations, smaller ion species have both an advantage and a disadvantage. The smaller, cooler QGP might be shorter than for PbPb collisions.
  - The reduced quenching means that the nuclear mass. The reduced quenching means that the smaller, cooler QGP might be shorter than for PbPb collisions.
  - Higher luminosities would translate to a larger reach in equivalent luminosity. We then evaluated the standard deviation of the systematic uncertainty on the impact of standard quenching for the purpose of producing Fig. 5.
  - The result of Eq. (1) is shown as a function of the value for a given collider setup.
  - The procedure that we envisage for this purpose is to determine the expectations for full quenching and to use measurements of the reconstructed top jet transverse momentum in Fig. 6.
  - The average total coherence delays and the time-induced difference of all heavy-ion events from full quenching of the mass were quenching of the jets in events.
  - The average total delay time ($\tau_{\text{tot}}$) is shown as a function of the time structure of the QGP medium.

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**Diagram Notes:**
- **QGP**
- **Time (fm/c)**
- **Graph Title:** Boosted Tops: time delayed probe
- **Graph Text:**
  - Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times
- **Graph Axes:**
  - X-axis: $p_{t,\text{top}}^{\text{reco}}$ (GeV)
  - Y-axis: $\langle t_{\text{tot}} \rangle$ (fm/c)
- **Graph Lines:**
  - Solid line: Total delay time and std. dev ($\tilde{q} = 4 \text{ GeV}^2 \text{ fm}^{-1}$)
  - Green line: Coherence Time
  - Blue line: W decay Time
  - Red line: Top decay Time
  - Dotted line: Total delay time ($\tilde{q} = 1 \text{ GeV}^2 \text{ fm}^{-1}$)
Boosted Tops: time delayed probe

- Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times

![Diagram showing contributions to the average total delay time](image)

**Contributions to the average total delay time,**

- contributions to the average total delay time (eq. 18)

**FIG. 6. Total delay time and its standard deviation (marked by vertical black lines).** To illustrate the weak dependence of the sum of the three components is also represented as a dashed line. The range of dashed line is shown as coloured stacked bands (see legend). For comparison, the top decay time and W decay time of all events are also shown.

**Top decay Time**

**W decay Time**

**Total delay time and std. dev (eq. 18)**

**Control of the jet energy scale**

**Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times.**
Boosted Tops: time delayed probe

- Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times

![Graph showing time-delayed probe results](image)

- The result of Eq. (1) is shown as a function of the total delay time assuming a dependence of $\hat{q}$ = 4 GeV fm$^{-1}$.

- The procedure for this purpose is to determine the expectations for full quenching and to apply that determination to embedded measurements of the reconstructed top jet transverse momentum in Fig. 6, as vertical black lines.

- To illustrate the weak dependence of potential future colliders [38, 39], the dispersion bands are shown. The range of $p_{T,\text{top reco}}$ is shown as stacked bands (see legend).

- The result for $q$ = 1 GeV fm$^{-1}$ is shown as a dashed line. The larger control of the jet energy scale is achieved with lighter species that in Fig. 5 we show a smaller, cooler QGP is also likely to result in less quenching that goes as less than 15%, in line with observations in CuCu [35] that are consistent with quenching that goes as less than 15%.

- At low luminosities the extra factor is relatively limited, about 1 order of magnitude larger than for PbPb.

- The reduced quenching means that the lifetime of the nuclear mass is increased to about 3. Note that at higher luminosities it increases to about 3. This guides our choice of possible $q$ values across many replicas. The result for the systematic and cross-calibration uncertainty between PbPb and pp collisions.

- One should keep in mind that other jet-energy scale uncertainties that are common to the pp and PbPb scenarios. At low luminosities the extra factor is relatively limited, about 1 order of magnitude larger than for PbPb, in part because of the reduction of electromagnetic effects such as bound–free pair production [37]. Generically, higher luminosities would cause of the reduction of electromagnetic effects such as bound–free pair production [37]. Generically, higher luminosities would cause of the reduction of electromagnetic effects such as bound–free pair production.
Boosted Tops: time delayed probe

Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times.

[Diagram showing the relationship between the reconstructed top jet transverse momentum and the total delay time.]

To estimate the potential precision of such an approach, we examined how well the average contribution of each component translates to a larger reach in lifetime.

[Graph showing the total delay time and its standard deviation (marked with error bars) for q, w, and b quarks, with corresponding ranges for different luminosities (pp, KrKr, PbPb) and q values (1 GeV^2/fm^4, 4 GeV^2/fm^4).]
Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times.
Boosted Tops: time delayed probe

- Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times.
Boosted Tops: FCC vs LHC

- Reconstructed W Mass as a function of the top $p_T$:

- Useful probe of the QGP density evolution

- QGP tomography:

- FCC: able to scan entire QGP lifetime!

![Graph showing reconstructed W mass as a function of top $p_T$ comparing FCC and LHC, with different time scales and quenching effects.](image)
Boosted Tops: FCC vs LHC

- Reconstructed W Mass as a function of the top $p_T$:
- Useful probe of the QGP density evolution
- QGP tomography:
- FCC: able to scan entire QGP lifetime!
- HE-LHC: Limited discrimination between short vs long lived medium…
Nowadays, we have ways of constraining:
- Later times
- Initial times
Probing QGP time evolution

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  - Need something:
    - To slice/probe different QGP timescales more directly
Probing QGP time evolution

✦ Nowadays, we have ways of constraining:
  ✦ Later times
  ✦ Initial times

✦ Need something:
  ✦ To slice/probe different QGP timescales more directly
  ✦ A channel that is easily (and frequently) produced
Probing QGP time evolution

- Nowadays, we have ways of constraining:
  - Later times
  - Initial times

- Need something:
  - To slice/probe different QGP timescales more directly
  - A channel that is easily (and frequently) produced
  - Easily implemented at both RHIC and LHC
Jets and QCD

- Jets: a space-time evolving structure that is the result of a QCD parton shower
- Collection of multiple parton emissions, that take place iteratively (until hadronization energy scale)
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Formation Time

- Time interval needed for the gluon to be radiated from a quark (and act as a new source of particles)
- Estimated as a life-time of a virtual quark+gluon state (p+k):

Heisenberg uncertainty: \( \Delta t \sim \frac{1}{\Delta E} \sim \frac{1}{m_{\text{virtual}}} \)

+ Lorentz boost: \( \Rightarrow \tau_{\text{form}} = \frac{E}{m_{\text{virtual}}^2} \)

\[ m_{\text{virtual}}^2 = 2p \cdot k = 2z(1 - z)E^2(1 - \cos \theta) \simeq z(1 - z)E^2\theta^2 \]

\[ \Rightarrow \tau_{\text{form}} = \frac{1}{z(1 - z)E\theta^2} \]
Jets: multiscale probe

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In principle, jets have all the possible timescales
Jets in the QGP

- One could, potentially assess all time evolution of the QGP
- How? Recluster splittings by formation time!
Jets in the QGP

- One could, potentially assess all time evolution of the QGP
- How? Reclasser splittings by formation time!
- Generalised $k_T$ jet algorithm with $p = 0.5$:

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p_{t,i}^{2p}$$

$p = 0.5$: $d_{ij} \sim p_{T,i} \frac{\Delta R_{ij}^2}{R^2} \sim p_T \theta^2 \sim \frac{1}{\tau_{form}}$

$$\left( \tau_{form} = \frac{1}{z(1-z)E\theta^2} \right)$$
Jets in the QGP

- One could, potentially assess all time evolution of the QGP
- How? Recluster splittings by formation time!
- Generalised $k_T$ jet algorithm with $p = 0.5$:

\[
\begin{align*}
    d_{ij} &= \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p_{t,i}^{2p} \\
    p &= 0.5: \quad d_{ij} \sim p_{T,i} \frac{\Delta R_{ij}^2}{R^2} \sim p_T \theta^2 \sim \frac{1}{\tau_{\text{form}}} \\
\end{align*}
\]

\[
\left( \tau_{\text{form}} = \frac{1}{z(1-z)E\theta^2} \right)
\]

$\theta_1 >> \theta_2 >> \theta_3 \ldots : \tau_1 \lessapprox \tau_2 \lessapprox \tau_3 \ldots$
Jets in the QGP

✦ One could, potentially assess all time evolution of the QGP
✦ How? Recluster splittings by formation time!
✦ Generalised $k_T$ jet algorithm with $p = 0.5$:

$$d_{ij} = \min(p^{2p}_{t,i}, p^{2p}_{t,j}) \frac{\Delta R_{ij}^2}{R^2} \quad d_{iB} = p^{2p}_{t,i}$$

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$$\theta_1 \gg \theta_2 \gg \theta_3 \ldots : \tau_1 \approx \tau_2 \approx \tau_3 \ldots$$

Reclustering:
from large to small $\tau_{form}$
Jets in the QGP

✦ One could, potentially assess all time evolution of the QGP

✦ How? Recluster splittings by formation time!

✦ Generalised kₜ jet algorithm with p = 0.5:

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\[ (\tau_{\text{form}} = \frac{1}{z(1-z)E\theta^2}) \]

\[ \theta_1 \gg \theta_2 \gg \theta_3 \ldots : \quad \tau_1 \leq \tau_2 \leq \tau_3 \ldots \]

Reclustering:
from large to small \( \tau_{\text{form}} \)

Unclustering:
First uncluster: smallest \( \tau_{\text{form}} \)
Jet Splitting function

- Unclustering jet and selecting different $\tau_{\text{form}}$:

$$\tau_{\text{form}} = \frac{1}{z(1-z)E\theta^2}$$

Medium model:
- JEWEL 2.2.0 without recoils
- Pre-defined simple medium model for PbPb
  $\sqrt{s_{\text{NN}}} = 5.02$ TeV centrality: [0-10]%
- Hadron level
Jet Splitting function

- Unclustering jet and selecting different $\tau_{\text{form}}$:

\[ z = \frac{p_{T,2}}{p_{T,2} + p_{T,1}} \]

\[ \tau_{\text{form}} = \frac{1}{z(1-z)E\theta^2} \]

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- Unclustering jet and selecting different $\tau_{\text{form}}$:

![Graph showing jet splitting function with different $\tau$ values and corresponding distributions.](image)

Legend:
- Blue: Vacuum ($\tau < 2.5$ fm)
- Dotted blue: Vacuum ($\tau > 5.0$ fm)
- Red: Medium ($\tau < 2.5$ fm)
- Dotted red: Medium ($\tau > 5.0$ fm)

*Preliminary*
Jet Splitting function

Unclustering jet and selecting different $\tau_{\text{form}}$:

Modification is larger for small $\tau_{\text{form}}$
(first splittings)
Jet Splitting function

Unclustering jet and selecting different $\tau_{form}$:

Modification is larger for small $\tau_{form}$ (first splittings)

Comparing the average value of the distribution:
Medium/Vacuum ratio

*Preliminary*
Jet Splitting function

- Unclustering jet and selecting different $\tau_{\text{form}}$:

\[
\begin{align*}
\frac{<\xi_{\text{med}}>}{<\xi_{\text{vac}}>} & = \log(1/z) \\
\tau & \text{ can be related to the medium density (at that timescale)}
\end{align*}
\]
Jet Splitting function

- Unclustering jet and selecting different $\tau_{\text{form}}$:

\[ \begin{array}{c}
\text{Jet Splitting function} \\
\text{0} \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \\
\tau \quad (\text{fm}) \\
\end{array} \]

Other (more natural) reclustering have also the same trend
Reclustering by $\tau_{\text{form}}$ more sensitive (as expected)
Unclustering vs Monte Carlo

Let’s start by what we know (PYTHIA 8.2) and track formation time at the Monte Carlo to compare with unclustering:
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As we go further into the unclustering, we deviate more from the original parton shower timescale.
Let's start by what we know (PYTHIA 8.2) and track formation time at the Monte Carlo to compare with unclustering:

As expected, vacuum jets have only a few splittings inside the medium.
Unclustering vs Monte Carlo

- Long dispersion in formation times...
- Correlation is not the best one ~[35-40]%…
  
  But it seems better when using $\tau_{\text{form}}$ instead of C/A
- Large ISR and Hadronization contamination…

*Preliminary*
Unclustering vs Monte Carlo

- Long dispersion in formation times…
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- It may happen a wrong identification of the branch…
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Summary

- Strong need to evaluate the QGP space-time evolution.
- Use of jet substructure to access parton shower formation time seems possible
Summary

✦ Strong need to evaluate the QGP space-time evolution.
✦ Use of jet substructure to access parton shower formation time seems possible
✦ Several challenges ahead:
  ✦ Matching between parton branch and reconstructed sub-jet (universality across different models)
  ✦ Accurate extraction of the timescale of each splitting (MC parton shower not ordered in $\tau_{\text{form}}$)
  ✦ Experimental feasibility yet to be assessed
Summary

- Strong need to evaluate the QGP space-time evolution.
- Use of jet substructure to access parton shower formation time seems possible
- Several challenges ahead:
  - Matching between parton branch and reconstructed sub-jet (universality across different models)
  - Accurate extraction of the timescale of each splitting (MC parton shower not ordered in $\tau_{\text{form}}$)
  - Experimental feasibility yet to be assessed
- Work in progress…

Thank you!
Acknowledgements
Backup Slides
Lund Plane

*Preliminary*

JEWEL (Simple) \( \tau \)

Soft

Hard

Long

Short

Hard

JEWEL Simple \( \tau \)

Collinear

Wide

Collinear

Wide
Lund Plane

$dN/d\xi$

Simple ($\tau < 2.5$ fm)

Simple ($\tau > 5.0$ fm)

*Preliminary*

$\xi = \log(1/z)$

$\log(R/10)$

$\log(1/\tau)$

$\tau$

JEWEL (Simple - Vac) C/A

JEWEL (Simple - Vac) $k$

L. Apolinário
Lund Plane

- Comparison of the primary Lund Plane with reclusters algorithms (k_T, C/A and τ_{form})

- Medium-modified jets (JEWEL, no recoils)

Comparison of the primary Lund Plane with reclusters algorithms (k_T, C/A and τ_{form})

Medium-modified jets (JEWEL, no recoils)
Lund Plane

- Comparison of the primary Lund Plane with reclusters algorithms ($k_T$, C/A and $\tau_{form}$):
- Medium-modified jets (JEWEL, no recoils) vs Vacuum jets

JEWEL (Simple - Vac) $k_T$

JEWEL (Simple - Vac) C/A

JEWEL (Simple - Vac) $\tau$

Collinear

Wide
Lund Plane

- Comparison of the primary Lund Plane with reclusters algorithms (kT, C/A and \( \tau_{\text{form}} \)):
  - Medium-modified jets (JEWEL, no recoils) vs Vacuum jets