Time evolution of a medium-modified jet

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Special thanks to:
Ruben Conceição, Guilherme Milhano and Jesse Thaler

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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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  Jets, Quarkonia (hard probes),…
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⇒ Need strategies to probe the time-structure 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

[Andrés et al (19)]

Switching off quenching during the first 0.6 fm/c
Time probing of the QGP

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(boosted tops)

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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 its standard deviation as a function of reconstructed top jet transverse momentum.](image)

- The result of Eq. (1) is shown as a function of the quark transverse momentum in Fig. 6, as vertical black lines. To illustrate the weak dependence of the sum of the three components, the total delay time for \( \langle \tau_{\text{tot}} \rangle \) is shown as coloured stacked bands (see legend). For comparison, the total delay time was also calculated for different quark masses (\( q = 1, 4 \text{ GeV}^2 \text{ fm}^{-1} \)).

- The procedure that we envisage for this purpose is to control the jet energy scale \( \tau_{\text{h}} \), the average total delay time \( \langle \tau_{\text{tot}} \rangle \), and the coherence time \( \tau_{\text{coh}} \) associated with lighter species that in Fig. 5 we show a different value for PbPb events from full quenching results.

- Ref. \[34\] from CMS gives a projection for the uncertainties on the expected standard quenching results start to dominate, since we have taken them to be independent of the PbPb equivalent luminosity. However, at low luminosities the extra factor is relative to the larger system. Therefore, the systematic uncertainty on the impact of standard quenching for the purpose of producing Fig. 5.

- Aside from luminosity considerations, smaller ion collisions have both an advantage and a disadvantage. The advantage is that the intrinsic time scales associated with heavier ions are longer than for PbPb, in part because of the extra factor in the nuclear mass. The reduced quenching means that the early times would be later than for PbPb, in part because of the quark mass. However, a disadvantage is that the intrinsic time scales associated with lighter species have both an advantage and a disadvantage. The advantage is that the time scales associated with lighter species have a smaller, cooler QGP might be shorter than for PbPb. However, a disadvantage is that the intrinsic time scales associated with heavier ions are longer than for PbPb, in part because of the extra factor in the nuclear mass. The reduced quenching means that the early times would be later than for PbPb.
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 for various components](image)

- Total delay time and standard deviation for hh events (\(\bar{q} = 4 \text{ GeV}^2 \text{ fm}^{-1}\))
  - Green: Coherence Time
  - Blue: W decay Time
  - Red: Top decay Time

- Total delay time (\(\bar{q} = 1 \text{ GeV}^2 \text{ fm}^{-1}\))

![Diagram showing QGP and jets](image)

- QGP
- Jets: t, b, q, qbar
- Time (fm/c)
- Low Pt top reco

Additional notes:
- Semi-leptonic decay of ttbar events produce jets that start interacting with the QGP only at later times.
- To estimate the potential precision of such an approach, one needs to consider the systematic and scale uncertainties that are common to the pp and PbPb scenarios. At low luminosities the extra factor is relevant, while at high luminosities the intrinsic time scales associated with top-quark probes have both an advantage and a disadvantage. The advantage is that the intrinsic time scales associated with top-quark probes are longer than for PbPb, while the disadvantage is that the intrinsic time scales associated with top-quark probes are shorter than for PbPb. However, a disadvantage is that the intrinsic time scales associated with top-quark probes are shorter than for PbPb, while the disadvantage is that the intrinsic time scales associated with top-quark probes are longer than for PbPb.
Boosted Tops: time delayed probe

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![Graph showing the time delay and quenching effects](Image)

- The procedure envisaged for this purpose is to first apply that determination to embedded objects to determine the expectations for full quenching and to use measurements of the final state to reconstruct jets with cleanly identified (leptonic) parts.

- It is crucial to have a reliable estimate of the expected values for a given collider setup.

- The result of Eq. (1) is shown as a function of the average total delay time and standard deviation for two values of $\hat{q}$, as vertical black lines. To illustrate the weak dependence of the sum of the three components on $\hat{q}$, the total delay time for $\hat{q} = 1 \text{ GeV}^2 / \text{fm}$ is shown as a dashed line. The range of $\langle \tau_{\text{top}} \rangle$ is shown as coloured stacked bands (see legend).

- For comparison, the total delay time for $\hat{q} = 4 \text{ GeV}^2 / \text{fm}$ is also represented as a curve in the graph.

- The average contribution of each component is determined by coherence delays and the jet energy scale. Only jets that start interacting with the QGP only at later times contribute to the final state, and so more accessible with top-quark probes. However, as the smaller, cooler QGP might be shorter than for PbPb, it increases to about 3. Note that at higher luminosities, the systematic and other uncertainties are relatively limited, about 1%.

- Aside from luminosity considerations, smaller ion collisions (i.e. total number of hard collisions) that are up to an order of magnitude larger than for PbPb, in part because of the up to 8 times more effective nucleon-nucleon luminosities such as bound–free pair creation, expected standard quenching results start to dominate.

- Since we have taken them to be independent of the PbPb events, the extra factor is relatively limited, about 1% for the systematic uncertainty on the impact of standard quenching for the purpose of producing Fig. 5. However, for the full quenching case, the systematic uncertainty on the impact of standard quenching is 10%.

- Following the recent successful XeXe machine development run at the LHC, the prospect has been raised that with ions lighter than Pb it might be possible to achieve equivalent luminosity. While the systematic uncertainty on the impact of standard quenching is 10%, standard deviation was 1% for the systematic uncertainty on the impact of standard quenching across many replicas. The result for the average total delay time was consistent with quenching that goes as $1/t$.

- The smaller, cooler QGP is also likely to result in less quenching in events from full quenching that goes as $1/t$. This guides our choice of $\hat{q}$ for the purpose of illustrating the tradeoff between quenching and the expected standard quenching results.

- Ref. [34] from EPS-HEP 2019.
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 the relationship between reconstructed top jet transverse momentum and time delay](image)

- The procedure that we envisage for this purpose is to take into account the long-range QGP evolution. It is for the purpose of illustrating the trade-off associated with lighter species that in Fig. 5 we show a characteristic time structure of the QGP medium.

- The smaller, cooler QGP might be shorter than for PbPb, but the intrinsic time scales associated with ttbar production are much longer. Thus a smaller, cooler QGP is also likely to result in less quenching. It is for the purpose of illustrating the trade-off associated with lighter species that in Fig. 5 we show a characteristic time structure of the QGP medium.
Boosted Tops: time delayed probe

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

Graphical representation:

- The graph shows the average total delay time \( \langle \tau_{\text{tot}} \rangle \) as a function of the reconstructed top jet transverse momentum \( p_{t,\text{top}}^{\text{reco}} \) (GeV).
- Different lines represent total delay time and standard deviation (\( q = 4 \text{ GeV}^2 \text{ fm}^{-1} \)), coherence time, W decay time, and top decay time.
- The figure illustrates the trade-off between quenching of jets and the need for high luminosities to study them.

**Notes:**

- The control of the jet energy scale is crucial.
- The range of values for a given collider setup is shown.
- The dispersion and systematic effects from the CMS machine are indicated.
- The figure shows the expected standard quenching results.
- The CMS gives a projection for the uncertainties on the equivalent luminosity.
- The result for \( \hat{q} = 1 \text{ GeV}^2 \text{ fm}^{-1} \) is also represented.

**Equation:**

\[ \tau_{\text{tot}} = \tau_{\text{coh}} + \tau_{\text{W decay}} + \tau_{\text{top decay}} \]

**Legend:**

- Total delay time and std. dev (\( \hat{q} = 4 \text{ GeV}^2 \text{ fm}^{-1} \))
- Coherence Time
- W decay Time
- Top decay Time
- Total delay time (\( \hat{q} = 1 \text{ GeV}^2 \text{ fm}^{-1} \))

**Discussion:**

- To be able to identify the time-induced di
- The total delay time for \( \hat{q} = 4 \text{ GeV}^2 \text{ fm}^{-1} \) is shown as coloured stacked bands (see legend).
- The larger spread in the bands indicates the higher uncertainty at higher luminosities.
- The smaller, cooler QGP might be shorter than for PbPb collisions.
- Higher m
- Lighter ions associated with lighter species that in Fig. 5 we show a significant advantage.
- The machine used was KrKr.
- The method used a quenching of 10% rather than 15%, in line with observations in CuCu that are expected to be less than 15%.
- The figure shows the average contribution of each component.
- The systematic and scale uncertainties that are common to the pp and PbPb collisions are considered.
- The DIS dependence of the sum of the three components is also represented.
- The dispersion of potential future colliders is considered.
- The range of values for a given collider setup is shown.
- The CMS gives a projection for the uncertainties on the equivalent luminosity.
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**Conclusion:**

- The figure illustrates the trade-off between quenching of jets and the need for high luminosities to study them.
- The control of the jet energy scale is crucial.
- The range of values for a given collider setup is shown.
- The dispersion and systematic effects from the CMS machine are indicated.
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**Further Reading:**

- [Apolinário et al (18)]
- [20] from ATLAS, shows a 1% increase in the standard deviation.

**Graph:**

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![Graph showing total delay time and its standard deviation](Image)

1. 75 = 4 GeV² fm⁻¹
2. Total delay time and std. dev (q̃ = 4 GeV² fm⁻¹)
3. Coherence Time
4. W decay Time
5. Top decay Time
6. Total delay time (q̃ = 1 GeV² fm⁻¹)

<sub>[Apolinário et al (18)]</sub>
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!

Boosted Tops: FCC vs LHC

[Apolinário et al (18)]
Boosted Tops: FCC vs LHC

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- 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…

![Graph showing reconstructed W mass as a function of the top $p_T$ for HE-LHC and FCC with different quenching scenarios.](image-url)
Probing QGP time evolution

- Nowadays, we have ways of constraining:
  - Later times
  - Initial times
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Probing QGP time evolution

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✦ Nowadays, we have ways of constraining:
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  ✦ Need something:
    ✦ To slice/probe different QGP timescales more directly
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  ✦ A channel that is easily (and frequently) produced
Probing QGP time evolution

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  - Initial times
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  - 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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It takes time to emit a parton...
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? Reccluster splittings by formation time!
Jets in the QGP

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

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

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

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

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✧ Generalised $k_T$ jet algorithm with $p = 0.5$:

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

$$\theta_1 \gg \theta_2 \gg \theta_3 \ldots : \tau_1 \lesssim \tau_2 \lesssim \tau_3 \ldots$$
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- How? Recluster splittings by formation time!
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$$\left( \tau_{form} = \frac{1}{z(1-z)E\theta^2} \right)$$

$$\theta_1 >> \theta_2 >> \theta_3 \ldots \quad \tau_1 \simeq \tau_2 \simeq \tau_3 \ldots$$

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

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

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

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

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

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

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

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

$$
\tau_{\text{form}} = \frac{1}{z(1-z)E\theta^2}
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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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Medium model:
- $\xi = \log(1/z)$
- Preliminary
Jet Splitting function

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

<table>
<thead>
<tr>
<th>$\xi$</th>
<th>dN/d$\xi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>

- Graph showing distributions for different $\tau$ values:
  - Vacuum ($\tau < 2.5$ fm)
  - Vacuum ($\tau > 5.0$ fm)
  - Medium ($\tau < 2.5$ fm)
  - 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)

1. **Jet Splitting function**

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

- Vacuum ($\tau < 2.5$ fm)
- Vacuum ($\tau > 5.0$ fm)
- Medium ($\tau < 2.5$ fm)
- Medium ($\tau > 5.0$ fm)

*Preliminary*
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```

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

```
<table>
<thead>
<tr>
<th>$\xi$ = log(1/z)</th>
<th>(dN/d\xi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>1</td>
<td>0.20</td>
</tr>
<tr>
<td>2</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td>0.05</td>
</tr>
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</table>

Varying $\tau$:
- Vacuum ($\tau < 2.5$ fm)
- Vacuum ($\tau > 5.0$ fm)
- Medium ($\tau < 2.5$ fm)
- Medium ($\tau > 5.0$ fm)

*Preliminary*
Jet Splitting function

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

\[
\frac{\langle \xi_{\text{med}} \rangle}{\langle \xi_{\text{vac}} \rangle}
\]

Can be related to the medium density (at that timescale)

*Preliminary*
Jet Splitting function

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

![Graph showing Jet Splitting function with different $\tau_{\text{form}}$ and $\tau_{\text{vac}}$ values.]

- Other (more natural) reclustering have also the same trend
- Reclustering by $\tau_{\text{form}}$ more sensitive (as expected)
Let's start by what we know (PYTHIA 8.2) and track formation time at the Monte Carlo to compare with unclustering:

Unclustering vs Monte Carlo

---

*Preliminary*
Let's start by what we know (PYTHIA 8.2) and track formation time at the Monte Carlo to compare with unclustering:

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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  ~[35-40]…
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- It may happen a wrong identification of the branch…

*Preliminary*
Unclustering vs Monte Carlo

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Thank you!
Acknowledgements
Backup Slides
Lund Plane

*Preliminary*

JEWEL (Simple) $\tau$

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EPS-HEP 2019
Lund Plane

![Graph showing the Lund Plane with different regions labeled as Soft, Hard, Long, and Short, and plots for JEWEL (Simple) and JEWEL (Simple - Vac) C/A, with preliminary notes marked.](image)

- JEWEL (Simple) τ
  - Soft
  - Hard
  - Long
  - Short

- JEWEL (Simple - Vac) C/A

- Graphs for Simple (τ < 2.5 fm) and Simple (τ > 5.0 fm)

*Preliminary*
Lund Plane

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

- Comparison of the primary Lund Plane with reclusters algorithms ($k_T$, C/A and $\tau_{\text{form}}$):

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