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Unveiling the yoctosecond structure of the QGP with top quarks

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Abstract

Top quarks have recently been measured for the first time in nuclear collisions. With most of the integrated luminosity of the LHC PbPb programme still to be recorded and promising projections for the future HL-LHC, HE-LHC or FCC, top quark observables will be measured with good precision and become an excellent probe of the QGP. We argue here that the unique properties of the top quark provide a new way to study differentially the space-time evolution of the medium created in heavy ion collisions. Top quarks decay almost exclusively into a W boson and a b quark. The finite lifetimes of the top and W particles and the time-delay in the interaction of the (colour-singlet) W-boson's decay products with the medium add up to a total time during which the top-decay system is unaffected by the QGP. The three times are correlated with the kinematics of the top quark, allowing the approximate determination of the time at which the interaction with the QGP begins. We carry out a simple Monte Carlo feasibility study and find that the LHC has the potential to bring first, limited information on the time structure of the QGP. More extensive studies will require larger luminosities (e.g. with ions lighter than lead), and/or the higher energies of a future HE-LHC or FCC.

Keywords: Quark-Gluon Plasma, Jet energy loss, Top quark, HE-LHC, Light Ions

1. Introduction

In heavy-ion collisions there is strong experimental evidence (see [1] for a review) for the formation of a hot and dense medium — the quark-gluon plasma (QGP). There are a range of complementary probes that span the medium, probing scales from a few GeV up to TeV scale. Despite their differences, they are always effectively sensitive to an integral over the whole medium evolution. In this manuscript, we present a proof-of-concept analysis to directly probe the time-structure of the QGP.

2. Time dependent energy loss

Probes sensitive to energy loss effects, such as di-jets or boson-jet pairs, are produced simultaneously with the collision and start to interact with the medium shortly after being produced. The hadronic decay

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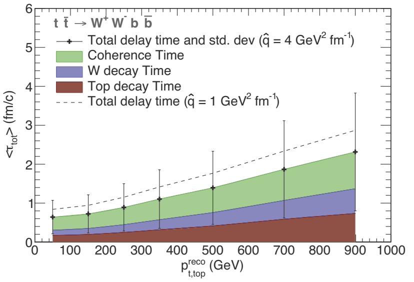

Fig. 1: Average contributions (in color bands) to the total delay time as given by eq. (1) and eq. (2) assuming a $\hat{q} = 4$ GeV^{2}fm^{-1}. The total delay time and its standard deviation are represented by the markers and corresponding error bars. The total delay time assuming a $\hat{q} = 1$ GeV^{2}fm^{-1} is shown as a dotted line.

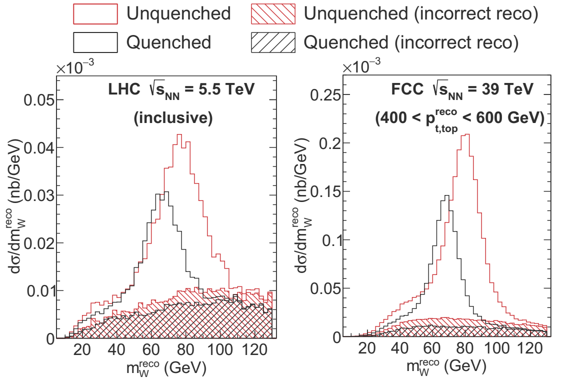

Fig. 2: Expected reconstructed cross-section of the $t\bar{t} \to W^+W^-b\bar{b} \to \mu\nu\, q\bar{q}\, b\bar{b}$ channel obtained at LHC (left) and FCC (right) as a function of the reconstructed W mass.

products of a top quark, however, will start interacting with the medium at later times. Namely, after the decay chain provided by a boosted top quark (with a proper lifetime of $\tau_{top} = 0.15$ fm/c) and subsequent W boson lifetime (with a proper lifetime given by $\tau_W = 0.1$ fm/c). This delay time can be further increased through colour coherence effects in the QGP. As shown in [2], coloured particles produced from a colour singlet state (as in the $W \to q\bar{q}$ decay channel) will remain colourless during a time,

$$\tau_d = \left(12/(\hat{q}\theta^2_{q\bar{q}})\right)^{1/3}, \tag{1}$$

where $\theta_{q\bar{q}}$ is the angle between the two outgoing quarks and $\hat{q}$ the transport coefficient parameter (translates the squared transverse momentum acquired per unit length when traversing a hot and dense medium). The average values of these contributions are shown as coloured bands in figure 1 as a function of the transverse momentum of the reconstructed hadronic top-quark jet ($p^{\text{reco}}_{t,top}$). It was assumed a transverse boost factor:

$$\gamma_{t,X} = \sqrt{p^2_{t,X}/m^2_X + 1}, \quad \text{where } X = \text{top or W}, \tag{2}$$

where m_X is the mass of the particle X. The total delay times, τ_{tot}, and their corresponding standard deviations are shown as vertical bars for $\hat{q} = 4$ GeV^2/fm. For comparison, the result that would be obtained assuming a $\hat{q} = 1$ GeV^2/fm is shown as a dotted line. To assess the experimental feasibility of measuring the time dependence of energy loss, we assume a simple scenario in which particles lose energy linearly proportional to the distance[1]. As such, for a fixed medium lifetime (τ_m), if particles lose 15% of their energy (E) when they traverse the full medium[2], the decay products of the W boson will lose only:

$$\Delta E/E\,(\tau_{tot}) = -0.15\ ((\tau_m - \tau_{tot})/\tau_m)\ \Theta(\tau_m - \tau_{tot}). \tag{3}$$

This τ_{tot}-dependent energy loss will result in a reconstructed W-candidate mass, m^{reco}_W, that depends on τ_{tot}. Experimentally this will manifest itself as a reconstructed W-candidate mass that depends on the reconstructed top-quark transverse momentum, $p^{\text{reco}}_{t,top}$, since the latter effectively determines $\langle\tau_{tot}\rangle$. To illustrate the feasibility of observing shifts in the reconstructed W mass, fig. 2 shows the simulated distribution of m^{reco}_W, in semi-leptonic events[3] at the LHC ($\sqrt{s_{NN}} = 5.5$ TeV, left panel) and for a Future Circular Collider (FCC, $\sqrt{s_{NN}} = 39$ TeV, right panel, for a given $p^{\text{reco}}_{t,top}$ bin). The red histograms represent what would be obtained by embedding (unquenched) $pp \to t\bar{t}$ events in lead-lead (PbPb) collisions, while the black histograms represent the results with full quenching, i.e., $\tau_{tot} = 0$ in Eq. (3).

[1] See the analytical results from computing the single medium-induced radiation spectrum in a diluting expanding medium [3].
[2] This approximation is based on the recent boson-jet results measured in lead-lead (PbPb) collisions at the LHC [4].
[3] For tagging purposes, the semi-muonic decay of a $t\bar{t}$ channel is ideal as it provides 2 b-jets and a muon. For details on the simulation setup and event reconstruction, please see [5].

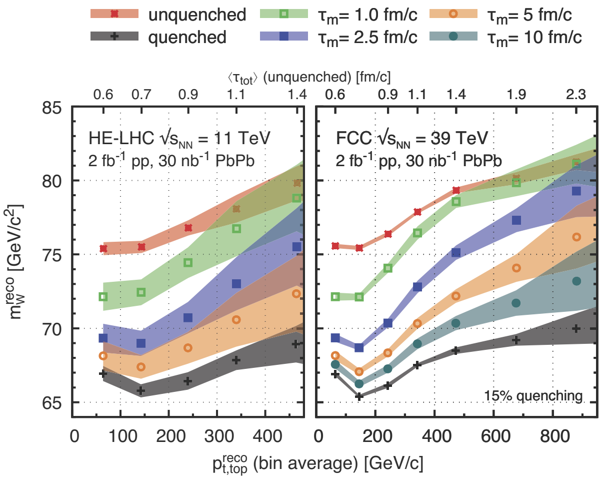

Fig. 3: Reconstructed W mass as a function of the reconstructed top p_t for the HE-LHC (left panel) and FCC (right panel). The shaded regions correspond to the 1σ statistical significance obtained from a replica analysis (see text for details). The different colours and markers correspond to the different QGP timescales shown as a label at the top of the figure and to the pp references embedded in a PbPb collision.

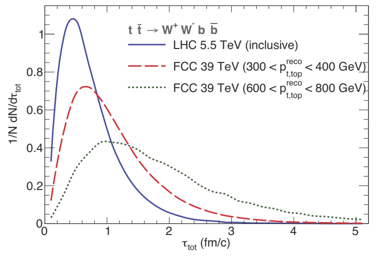

Fig. 4: Total delay time distributions obtained when using the full sample of $t\bar{t}$ events (in solid blue line), events where the reconstructed top has a transverse momentum $\in$ [300; 400] GeV (in dashed red line) and with a transverse momentum $\in$ [600; 800] GeV (in dotted green line).

3. Statistical feasibility assessment at the LHC and future colliders

To evaluate the ability of a given collider to distinguish different scenarios for τ_m, we adopt the following procedure. We extract the reconstructed W mass by performing a Gaussian fit on top of a linear background to account for the incorrectly reconstructed events (shown in fig. 2). This is done for multiple true-sized replica samples assuming an integrated luminosity of 2 fb^{-1} for the references (quenched and unquenched) and 30 nb^{-1} for PbPb (τ_m = 1 , 2.5 , 5 and 10 fm/c). In the latter, the W decay products lose energy as in eq. (3) while the remaining coloured particles are assumed to lose 15% of their energy. The resulting reconstructed W mass as a function of the $p^{\rm reco}_{t,top}$ is shown in fig. 3 considering the different QGP lifetimes for the FCC (right panel) and the high-energy upgrade of the LHC, designed to work at a $\sqrt{s_{NN}}$ = 11 TeV (left panel). The 1σ standard deviation resulting from such study, illustrated as a shaded region in fig. 3, includes reconstruction efficiency, b-tagging efficiency (assumed to be 70% per b), fluctuations from energy loss processes, medium subtraction procedures and finite detector resolution. Altogether, they were assumed to result in particle level fluctuations varying as $1/\sqrt{p_t}$ and scaled to give a 15% relative energy resolution for a p_T = 100 GeV jet (for further details see ref. [5]). The upper axis shows the average total delay time corresponding to the $p^{\rm reco}_{t,top}$ bin that is extracted from fig. 1. While at the FCC it would be possible to accurately extract the density evolution profile over the first timescales of the QGP, this reach becomes highly limited at lower centre-of-mass energies. To compensate for the lack of statistics in individual $p^{\rm reco}_{t,top}$ bins at lower centre-of-mass energies, we group together all events that pass the selection cuts, giving a sample that is largely inclusive with respect to the the total time delay (τ_{tot}). Distributions of τ_{tot} for an inclusive sample and samples with $p^{\rm reco}_{t,top}$ cuts are shown in fig. 4. Although the average delay time in the inclusive distribution is smaller than that in high $p^{\rm reco}_{t,top}$ bins, the large dispersion can still help bring sensitivity to the lifetime τ_m of the heavy-ion medium's quenching effects. Fig. 5 shows the results for the reconstructed W mass (and its corresponding 1σ statistical uncertainty band) integrated over $p^{\rm reco}_{t,top}$ and as a function of the PbPb luminosity for the same QGP timescales considered in fig. 3. The left (right) panel shows the results for LHC (HE-LHC). The quenched and unquenched references have a fixed luminosity of 2 fb^{-1} pp equivalent. From this plot, it is possible to estimate the maximum τ_m that can be distinguished with 2σ from the fully quenched baseline as a function of the PbPb equivalent luminosity (to be read as preserving the same number

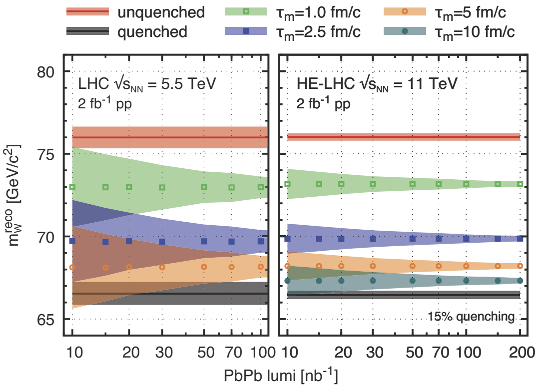

Fig. 5: Reconstructed W mass (integrated over $p_{t,top}^{\rm reco}$) as a function of the PbPb equivalent luminosity for the LHC (left panel) and HE-LHC (right panel). The shaded regions correspond to the 1σ statistical significance obtained from a replica analysis (see text for details). The different color and markers are the same as fig. 3.

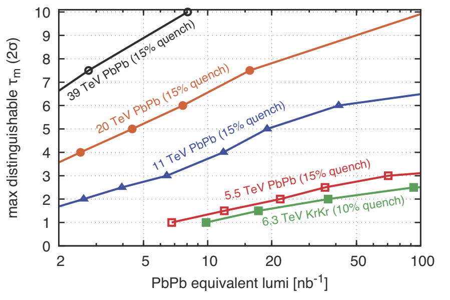

Fig. 6: Maximum QGP timescale that it is possible to distinguish from a fully quenched baseline with a 2σ significance as a function of PbPb equivalent luminosity for different $\sqrt{s_{NN}}$.

of nucleon-nucleon collisions). The results are shown in fig. 6 for different centre-of-mass energies. That figure also includes the expectations for a possible Krypton-Krypton (KrKr) collisional system, where the baseline for the energy loss is expected to be 10% [6]. While with the current LHC expectations (10 nb^{-1}) we are still limited to distinguish at most a scenario in which energy loss processes dominate over the first 1 fm/c, lighter ions could provide effective higher nucleon-nucleon luminosities that could compensate the smaller energy loss. E.g., a one (month) run of KrKr collisions (30 nb^{-1} of PbPb equivalent luminosity) could increase by 50% the maximum QGP timescales that could be probed already at the LHC. For future accelerator prospects please see [7].

4. Conclusions

Top quarks and their decays has a unique potential to resolve the time evolution of the QGP. In this work, we show a first attempt along this line of research by assessing the statistical significance of using the semi-muonic decay channel of a $t\bar{t}$ event. At FCC energies the results are very promising as it should be possible to assess the QGP density evolution with experimental control over different timescales (by using the p_t of the hadronic top). At HE/HL-LHC upgrade, although more limited, it should possible to distinguish different medium-duration scenarios/quenching dominated regions by using the inclusive top sample.

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