Resolving the time dimension in jet quenching studies of the QGP at the HL-LHC

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Abstract

One powerful probe of the quark-gluon plasma (QGP) is "jet quenching", i.e., the study of jet modifications while passing through the QGP. Processes used so far, e.g., dijet or Z/γ+jet production, are only sensitive to the properties of the QGP integrated over its lifetime. In this Letter, we point out that hadronically decaying W bosons can provide key novel insights into the time structure of the QGP when studied in events with a top-antitop ($t\bar{t}$) quark pair. As already demonstrated in Ref. [1] this is because of a "time delay" between the moment of the collision, hence the $t\bar{t}$ production and subsequent decay, and that when the W boson decay products start interacting with the QGP. More specifically, the scale of the time delay can be constrained by selecting on the reconstructed top quark transverse momentum, that is a unique feature. We propose to carry out more detailed Monte Carlo studies, e.g., taking advantage of improved jet quenching modeling and realistic physics-object reconstruction efficiencies. Although there seems to exist limited potential to bring the first information on the time structure of the QGP considering the baseline LHC scenario of Runs 3 and 4, lighter ions are potentially promising candidates despite their smaller quenching effects. Because of the potential for order-of-magnitudes higher effective integrated nucleon-nucleon luminosities, the Snowmass effort should answer whether there is an optimal nucleus-nucleus colliding system at HL-LHC. Substantially increased LHC partonic and photon-photon luminosities at HL-LHC (or future higher energy colliders) are independently proposed via isoscalar beams, even opening up opportunities for studies not accessible with high-pileup collisions. The high-luminosity collisions of isoscalar nuclei could provide a new environment to study the QGP and complement the QGP studies in the low-luminosity collisions of heavy nuclei.

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I. "UNVEILING THE YOCTOSECOND STRUCTURE OF THE QGP WITH TOP QUARKS"

Hydrodynamic simulation codes successfully predict a strong time dependence of the properties associated with the evolution of the quark-gluon plasma (QGP) in nucleus-nucleus collisions. High-multiplicity proton-proton (pp) and proton-nucleus collisions, i.e., systems with significantly smaller lifetimes than typically formed from heavy nuclei collisions, show also signatures suggestive of collective effects. Given the QGP lifetime is predicted to be about 10 fm at the LHC, it would be thus invaluable to devise an experimental method of probing this time dependence, that is a "chronometer" with yoctosecond time resolution.

When W bosons decay hadronically, the color singlet quark-antiquark pair is not immediately resolved by the strongly interacting medium, and only after a certain distance they start interacting independently. This "decoherence" time, τ_d, can be further enlarged when combined with the top-antitop ($t\bar{t}$) pair decay chain. At rest, top (t) quarks decay with a lifetime of $\tau_t \approx 0.15$ fm and the W boson has a lifetime of $\tau_W \approx 0.09$ fm. The sum of $\tau_t + \tau_W + \tau_d$ is correlated to the transverse momentum of the top quark (Fig. 1, left), a unique feature that can be exploited given a sufficient number of events. Therefore, the jets produced in the $t \to b + W$ decay chain experience only the part of the QGP after the sum of decay and decoherence times. In semileptonic $t\bar{t}$ events, the resulting high-p_T leptons, two b quarks, and missing transverse momentum are powerful tools for the identification ("tagging") of the signal process, rendering the $t\bar{t}$ process more attractive than, e.g., W+jet events.

We propose to build upon the existing knowledge (Fig. 1, right) and carry out more detailed Monte Carlo studies, e.g., taking advantage of improved jet quenching modeling [2] and realistic physics-object reconstruction efficiencies [3].

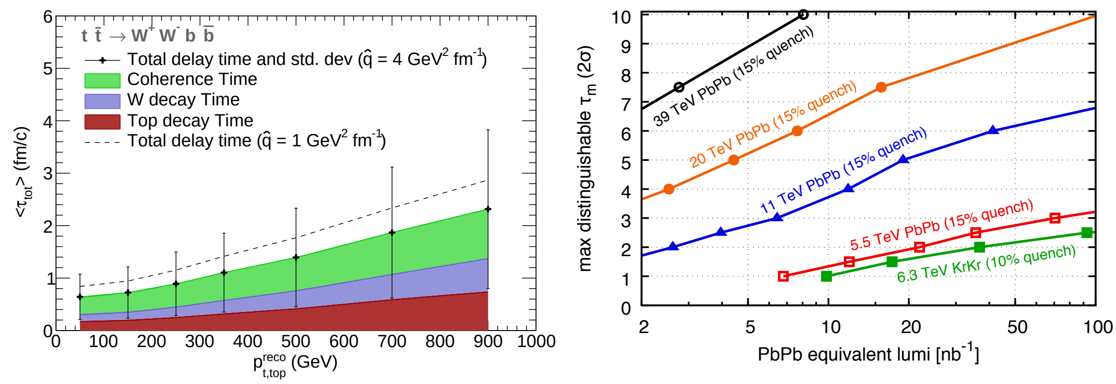

FIG. 1: (left) Total delay time, the average contribution of each component, and their standard deviation (markers and corresponding error bars) for different values of the transport coefficient $\hat{q}$. (right) The maximum quenching endtime that can be distinguished as a function of the integrated nucleus-nucleus luminosity for different collider energies and species. Figures from Ref. [1].

II. LIGHTER AND ISOSCALAR IONS

Following the recent successful studies with partially stripped xenon [4] ($^{129}Xe^{54+}$) and lead [5] ($^{208}Pb^{81+}$) beams in the SPS and LHC, two prospects have been raised: i) that with ions lighter than Pb [6, 7], and ii) reduction of the transverse emittance of the colliding ion [8]. Both are possible candidates—though method (ii) has yet to be demonstrated—to achieve effective nucleon-nucleon luminosities (i.e., total number of hard collisions) that are up to two orders of magnitude larger than for PbPb.

Higher luminosities would bring substantially increased sensitivity to the longer time structure of the QGP, while the lower intrinsic time scales associated with the smaller, cooler QGP in lighter ions are more accessible with the top quark "tag-and-probe" technique described in Section I. Aside from luminosity considerations, smaller ion species have, however, a potential disadvantage. A smaller, cooler QGP is also likely to result in less quenching. It is for the purpose of illustrating the tradeoffs associated with lighter species in Fig. 1. It should be noted that the curve labeled "KrKr" is shown as a simple scaling in the number of nucleon-nucleon collisions, therefore there is plenty of room in quantifying the prospects.

TABLE I: Representative beam parameters at the start of the highest luminosity physics fills—averages for ATLAS and CMS—in each annual PbPb runs (Ref. [6] and references therein) and machine development XeXe experiment with 16 bunches [4]. The original LHC design values for nucleus-nucleus collisions and future upgrade goals with PbPb [6] and isoscalar (with simple bunch intensity empirical scaling [7] and additionally including laser cooling [8]) beams are also shown. Emittance and the β function values at IPs are shown. Design, record achieved, and expected nucleon-nucleon luminosities are boxed.

Variable	Design	Achieved					Upgrade	$^{40}Ca^{20+}$ (cooling)
Year		2010	2011	2015	2017 (XeXe)	2018	≥2022	
Weeks in physics	—	4	3.5	2.5	—	3.5	4 (per run)	≥4
[TeV]	5.52	2.51		5.02	5.44	5.02	5.52	7
Bunch intensity [10^8]	0.7	1.2	1.1	2.0	2.8	2.2	1.9	30
Number of bunches	592	137	338	518	16	733	733–1240	1404
Pb norm. emittance ϵ_N[μm]	1.5	2.0	2.0	2.1	1.5	2.0	1.6	0.3
β^*[m]	0.5	3.5	1.0	0.8	0.3	0.5	0.5	0.15
NN luminosity [10^{30} cm^{-2} s^{-1}]	43	1.3	22.	156	465	264	303	42000
Pileup	—				—			5.5

III. SUMMARY

In this Letter, we propose to further study top quarks and their semileptonic decays in nucleus-nucleus collisions given the unique potential to resolve the time dimension in jet quenching studies of the QGP. At the LHC, with the currently planned luminosity, such a study requires a sufficiently large sample of top quarks. With significantly increased luminosity at the LHC (either from lighter or isoscalar ion species), the prospects for using jet quenching to study the evolution of the QGP over the first few fm are excellent and should be quantified in detail.

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