

Probing the Time Structure of the Quark-Gluon Plasma with Top Quarks

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 (Received 30 November 2017; revised manuscript received 27 March 2018; published 8 June 2018)

The tiny droplets of quark gluon plasma (QGP) created in high-energy nuclear collisions experience fast expansion and cooling with a lifetime of a few fm/c. Despite the information provided by probes such as jet quenching and quarkonium suppression, and the excellent description by hydrodynamical models, direct access to the time evolution of the system remains elusive. We point out that the study of hadronically decaying W bosons, notably in events with a top-antitop quark pair, can provide key novel insight into the time structure of the QGP. This is because of a unique feature, namely a time delay between the moment of the collision and that when the W -boson decay products start interacting with the medium. Furthermore, the length of the time delay can be constrained by selecting specific reconstructed top-quark momenta. We carry out a Monte Carlo feasibility study and find that the LHC has the potential to bring first limited information on the time structure of the QGP. Substantially increased LHC heavy-ion luminosities or future higher-energy colliders would open opportunities for more extensive studies.

DOI: [10.1103/PhysRevLett.120.232301](https://doi.org/10.1103/PhysRevLett.120.232301)

The quark-gluon plasma (QGP), a state that characterized the first microseconds of the Universe, is regularly produced and studied in ultrarelativistic heavy-ion collisions at both RHIC and the LHC. A range of complementary probes is used to study the QGP. These include properties that can be ascribed to hydrodynamic flow patterns, suppression of heavy-quark bound states, hadrochemistry of the final state, and modifications of the fragmentation of energetic partons that traverse the medium (see, e.g., Ref. [1]). A property common to all these probes is that they are sensitive to the properties of the QGP integrated over its lifetime.

Hydrodynamic simulation codes [2] predict a strong time dependence of the QGP's properties associated with its expansion and cooldown, which last about 10 fm/c at the LHC. It would be invaluable to develop a way of probing this time dependence. The recent discovery (see, e.g., Refs. [3,4] and references therein) that high-multiplicity proton-proton (pp) and proton-nucleus (pA) collisions show signatures suggestive of collective effects, in systems with significantly smaller lifetimes than typical PbPb or

AuAu collisions, is an additional motivation for devising a way of probing the time structure of the QCD medium.

One powerful probe of the QGP is “jet quenching,” i.e., the study of modifications of jets that pass through the QGP (see, e.g., Ref. [5]). In all hard processes used so far for this purpose, dijet, $\gamma + \text{jet}$ or $Z + \text{jet}$ production, the jets are produced *simultaneously* with the collision of the ions.

In this Letter, we point out that top-antitop ($t\bar{t}$) production offers a unique novel opportunity to study the quark-gluon plasma, in particular its time structure. This is because, at variance with all other jet measurements considered so far in the literature, the jets that come from the decay products of the W boson start interacting with the medium only at *later* times, due to a series of time delays [6]. At rest, top quarks decay with a lifetime of about $\tau_{\text{top}} \simeq 0.15$ fm/c and the W that is produced in the top-quark decay has a lifetime of about $\tau_W \simeq 0.09$ fm/c. When the W boson decays hadronically, the resulting color-singlet quark-antiquark ($q\bar{q}$) pair is not immediately resolved by the medium [9]. Only after the q and \bar{q} have propagated and separated a certain distance do they start interacting independently with the medium. We call this delay a decoherence time, τ_d . Thus, the jets that are produced in the $t \rightarrow b + W \rightarrow q\bar{q}$ decay chain do not see the full QGP, but only the part of the QGP that remains after the sum of decay and decoherence times. That sum of times is correlated to the momentum of the top quark, a feature that may be exploited given a sufficient number of events.

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To carry out a first investigation of the potential of using top quarks for probing the time structure of the QGP, we proceed as follows. We take the average total delay time before the W decay products start interacting with the medium to be

$$\langle \tau_{\text{tot}} \rangle = \gamma_{t,\text{top}} \tau_{\text{top}} + \gamma_{t,W} \tau_W + \tau_d, \quad (1)$$

For the decay times, we use a transverse boost factor, $\gamma_{t,X} = (p_{t,X}^2/m_X^2 + 1)^{1/2}$, defined in terms of the mass m_X , and transverse momentum $p_{t,X}$ of particle X . The transverse component is the natural choice, because the frame in which the top quark has no longitudinal momentum is also the one in which it is most natural to describe its interaction with the QGP, which is approximately longitudinally invariant. We take the average decoherence time to be [9]

$$\tau_d = \left(\frac{12}{\hat{q} \theta_{q\bar{q}}^2} \right)^{1/3}, \quad (2)$$

in natural units, $\hbar = c = 1$, and with $\theta_{q\bar{q}}$ the opening angle between the two decay products of the W , again in a longitudinal frame where the z component of W momentum is zero. The quantity \hat{q} is the transport coefficient of the medium (squared transverse momentum broadening per unit length, see, e.g., Ref. [5]). While in practice it is expected to be a function of time, for our proof of principle illustration here, we take it to be constant, $\hat{q} = 4 \text{ GeV}^2/\text{fm}$ (conservatively taken larger than found in Refs. [10,11]). To get an event-by-event estimate of the interaction start time, we will associate each component with a randomly distributed exponential distribution. With these choices, for inclusive top-quark production at the LHC with center-of-mass energy (per nucleon pair) $\sqrt{s_{NN}} = 5.5 \text{ TeV}$, the average times are, $\langle \gamma_{t,\text{top}} \tau_{\text{top}} \rangle \simeq 0.18$, $\langle \gamma_{t,W} \tau_W \rangle \simeq 0.14$, and $\langle \tau_d \rangle \simeq 0.34 \text{ fm}/c$, with dispersions that are comparable. The 1/3 power in Eq. (2), means that $\langle \tau_d \rangle$ is only weakly dependent on the value of \hat{q} .

To probe jet quenching and its time dependence in $t\bar{t}$ production, we here suggest measuring the invariant mass m_{jj} of the dijet system that is produced from hadronic W decays. In pp events, m_{jj} is closely related to the W mass, modulo final-state-radiation (FSR) effects. The difference in reconstructed m_{jj} in central ion-ion (AA) collisions as compared to pp will be our measure of jet quenching.

To evaluate the potential of such a study we examine semimuonic $t\bar{t}$ events, i.e., where one top decays to bW ($W \rightarrow \mu\nu$), while the other decays hadronically to bW ($W \rightarrow jj$). In pA collisions it has been demonstrated that it is possible to tag this class of events with essentially no background [12] as long as two b tags are required, and so we only consider signal events.

For a quantitative analysis, we use events from the ‘‘hvq’’ (heavy-quark) process [13] in revision 3180 of the POWHEGbox [14] generator, which simulates top-quark

production to next-to-leading (NLO) accuracy in the strong coupling constant. We use it with the PDF4LHC15_nlo_30 PDF set [15], and shower events with Pythia 8.223 [16,17], tune 4C [18]. Our final results will be based on events at the hadron level, without an underlying event. The number of events that we can expect for an integrated luminosity \mathcal{L}_{AA} of AA collisions is $n(f) \simeq \mathcal{L}_{AA} \sigma_{pp}^{(t\bar{t})} A^2 c(f)$, where $\sigma_{pp}^{(t\bar{t})}$ is the pp cross section for $t\bar{t}$ production and A is the atomic mass of the ions being collided (see also Ref. [19]). The $c(f)$ factor accounts for the centrality range f . We will concentrate on $f = 0\%–10\%$, and so use $c(0–10\%) \simeq 0.42$ [20].

To keep the analysis and simulation relatively simple, we choose not to embed events in a heavy-ion medium. Instead, we introduce a single factor to mimic the combination of all sources of fluctuations: those from the embedding and medium-subtraction procedure, from finite detector resolution, and also from jet quenching dynamics. Specifically, we rescale the momentum of each particle i by a factor $(1 + r\sigma_{p_i}/\sqrt{p_{t,i} + 1 \text{ GeV}})$, where r is a Gaussian-distributed random number (different for each particle) with a standard deviation of 1; σ_{p_i} is taken to be $1.5 \text{ GeV}^{1/2}$. This leads to an effective relative jet energy resolution of about $1.5 \text{ GeV}^{1/2}/\sqrt{p_t}$ for high- p_t jets, or about 15% for $p_t = 100 \text{ GeV}$, consistent with Ref. [21].

To simulate baseline full quenching in 0%–10% central PbPb systems, we apply a constant energy loss rescaling factor $\mathcal{Q}_0 = 0.85$ to all particle momenta, which is consistent with observations in $\gamma/Z + \text{jets}$ measurements performed by the ATLAS and CMS Collaborations [22,23]. Recall that the fluctuations associated with quenching are included in our single global fluctuation factor. A more sophisticated analysis would be possible, but is perhaps best carried out in the context of a full experimental study.

To account for dependence of the quenching on the time τ_{tot} at which the W decay products start to interact with the medium, all particles from the W decay are scaled by a factor $\mathcal{Q}(\tau_{\text{tot}})$ rather than \mathcal{Q}_0 . We will return to the exact form of $\mathcal{Q}(\tau_{\text{tot}})$ below.

To tag potential $t\bar{t}$ events, we require the presence of a muon, two b -tagged jets, and at least two non- b -tagged jets. The muon should have $p_t > 25 \text{ GeV}$ and rapidity $|y| < 2.5$. Jets are obtained using the anti- k_t jet algorithm [24] with radius $R = 0.3$ and subsequent partial declustering [25,26] with the k_t algorithm [27,28], all performed within FastJet v3.2.1 [29]. A selection requirement of $p_t > 30 \text{ GeV}$ and $|y| < 2.5$ is applied to the anti- k_t jets. We assume a b -tagging efficiency of $\epsilon_b = 70\%$ per b , as obtained in pPb events in Ref. [12] and anticipating the expected improvements in b tagging in high-multiplicity environments from HL-LHC detector upgrades [30,31]. We also assume that fake b tags do not introduce any substantial background.

Our W and top-quark reconstruction procedure is inspired by the pseudo-top definition of Refs. [32,33], adapted to be more resilient to the presence of additional jets from initial-state radiation (ISR) and at the same time robust with respect to effects of quenching on the energy scales of W and top candidates. The use of $R = 0.3$ anti- k_t clustering and then k_t declustering to obtain the input jets helps ensure adequate performance across a broad range of top-quark transverse boosts (similar in spirit though different in its details to Ref. [34]). The full procedure is detailed in the Supplemental Material [8].

For each event that satisfies the reconstruction requirements, we consider two observables: m_W^{reco} , the mass of the reconstructed hadronic W -boson candidate and $p_{t,\text{top}}^{\text{reco}}$, the p_t of the corresponding top candidate. The former will provide our measure of quenching (and was once before studied for this purpose [35]). The latter can be translated to an average τ_{tot} and for $200 \text{ GeV} \lesssim p_{t,\text{top}}^{\text{reco}} \lesssim 1 \text{ TeV}$ the relation reads (see Fig. 6 in the Supplemental Material [8])

$$\langle \tau_{\text{tot}} \rangle (p_{t,\text{top}}^{\text{reco}}) \simeq (0.37 + 0.0022 p_{t,\text{top}}^{\text{reco}} / \text{GeV}) \text{ fm}/c. \quad (3)$$

The distribution of τ_{tot} values is given in Fig. 1 for the LHC $\sqrt{s_{NN}} = 5.5 \text{ TeV}$, inclusively over $p_{t,\text{top}}^{\text{reco}}$, and for a future-circular collider (FCC) with $\sqrt{s_{NN}} = 39 \text{ TeV}$, considering events with $p_{t,\text{top}}^{\text{reco}} > 400 \text{ GeV}$. Note the long tails in both cases, which will contribute sensitivity to times substantially beyond $\langle \tau_{\text{tot}} \rangle$.

Figure 2 shows the distribution of m_W^{reco} , again for the LHC and FCC, with a $p_{t,\text{top}}^{\text{reco}}$ cut in the latter case. Results are shown with baseline full quenching for all particles and without quenching (the latter being equivalent to pp events embedded in heavy-ion events to account for the effect of the underlying event). One sees clear W -mass peaks, superposed on a continuum associated with events where the W decay jets have not been correctly identified. The continuum is significantly reduced at high $p_{t,\text{top}}^{\text{reco}}$. The W peaks in the quenched case are shifted to the left, and the extent of the shift provides an experimental measure of the

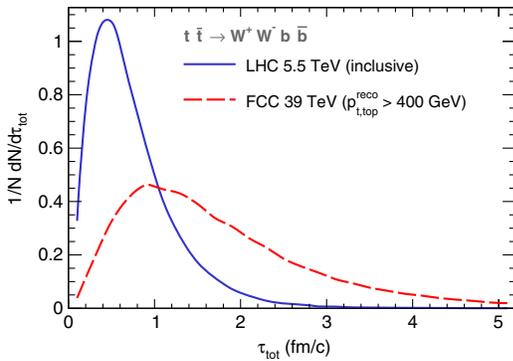


FIG. 1. Distribution of τ_{tot} for events that pass all reconstruction cuts and have a top-quark candidate (independently of the reconstructed top-quark and W -boson masses).

quenching. The peaks are also lower in the quenched case, reflecting the smaller fractions of events that pass the reconstruction (and, for FCC, $p_{t,\text{top}}^{\text{reco}}$ cuts).

To estimate the sensitivity of top-quark measurements to the time dependence of quenching in the medium, we consider a toy model in which the quenching is proportional to the time between the moment when the W decay products decohere, τ_{tot} , and a moment when the medium quenching effect stops being active, τ_m . This gives a τ_{tot} -dependent quenching factor $\mathcal{Q}(\tau_{\text{tot}})$ for the W decay products of

$$\mathcal{Q}(\tau_{\text{tot}}) = 1 + (\mathcal{Q}_0 - 1) \frac{\tau_m - \tau_{\text{tot}}}{\tau_m} \Theta(\tau_m - \tau_{\text{tot}}). \quad (4)$$

Recall that all other hadronic particles undergo quenching with the factor \mathcal{Q}_0 .

For each choice of τ_m we obtain a m_W^{reco} histogram as in Fig. 2. We carry out a binned likelihood fit for the histogram and the background of incorrectly reconstructed W 's using the functional form

$$N(m) = a \exp\left(-\frac{(m - m_W^{\text{fit}})^2}{2\sigma^2}\right) + b + cm, \quad (5)$$

which yields good fits. The free parameters a , b , c , σ , and m_W^{fit} are constrained to sensible ranges so as to increase the stability of the fit in low statistics samples.

Figure 3 shows the results for m_W^{fit} . They are plotted as bands for different τ_m values, as a function of the PbPb integrated luminosity, $\mathcal{L}_{\text{PbPb}}$. The width of each band represents the standard deviation of m_W^{fit} values that we obtain when we carry out fits for a large number of replica pseudoexperiments. Two of the bands are independent of the PbPb luminosity: the top, unquenched band, corresponds to the result that would be obtained by embedding 2 fb^{-1} of pp (unquenched) data into minimum-bias PbPb events. The bottom band is obtained by a similar procedure,

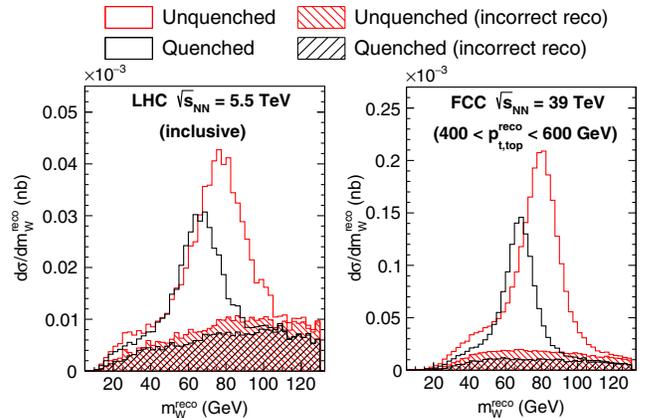


FIG. 2. Differential fiducial proton-proton $t\bar{t}$ reconstruction cross section as a function of m_W^{reco} at the LHC and FCC.

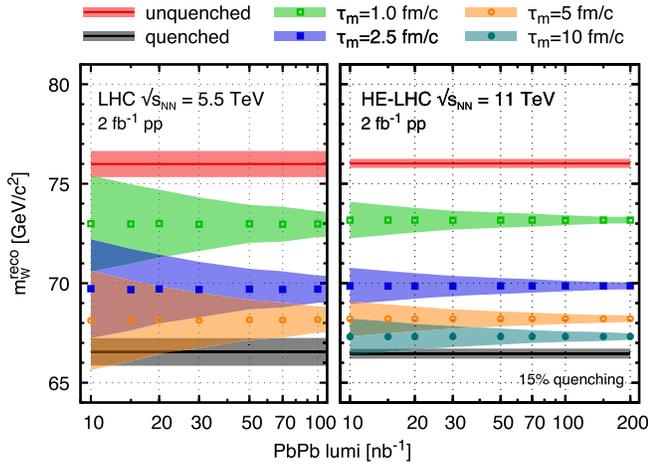


FIG. 3. The average (points) and standard deviation (width of band) for m_W^{reco} across many pseudoexperiments, as a function of luminosity for an inclusive sample of $t\bar{t}$ events, as a function of the integrated PbPb luminosity at the LHC (left) and the HE-LHC (right).

but with the pp jets' particles simply scaled down by the quenching factor \mathcal{Q}_0 , i.e., by the quenching factor that would be expected if the W decay products were present and started interacting from time 0. In a real experiment, the corresponding scaling factor could be obtained by measuring quenching in another quark-jet dominated process (e.g., with $\gamma + \text{jet}$ or $Z + \text{jet}$ balance), as a function of the jet p_t .

For short values of the effective medium lifetime, τ_m , the m_W^{fit} result is close to the unquenched result. This reflects the fact that the W decay products start interacting only towards the end of the medium lifetime. For larger values of τ_m they instead still see most of the medium duration, and most of the quenching. A very short-lived medium, $\tau_m = 1$ fm/c, could be distinguished from the full quenching baseline at the LHC with its currently approved $\mathcal{L}_{\text{PbPb}} = 10 \text{ nb}^{-1}$. However, to distinguish larger values of τ_m would require either higher luminosities or higher energies. This is illustrated in the right-hand plot of Fig. 3 for a future HE-LHC ($\sqrt{s_{NN}} = 11$ TeV), where the $t\bar{t}$ cross section is 6 times larger.

At higher-energies it becomes advantageous to explore the $p_{t,\text{top}}^{\text{reco}}$ dependence of m_W^{fit} , illustrated in Fig. 4 for the HE-LHC and the FCC ($\sqrt{s_{NN}} = 39$ TeV). For each bin of $p_{t,\text{top}}^{\text{reco}}$, the upper axis shows the corresponding average τ_{tot} . For a given band of τ_m , when $p_{t,\text{top}}^{\text{reco}}$ is large enough so that $\langle \tau_{\text{tot}} \rangle \gtrsim \tau_m$, the band merges with the unquenched expectation. Thus the shape of the $p_{t,\text{top}}^{\text{reco}}$ dependence gives powerful information on the medium time structure. (The unquenched and baseline-quenched bands also have a $p_{t,\text{top}}^{\text{reco}}$ dependence, induced by the underlying jet and muon p_t cuts, as well as different amounts of final-state radiation outside the $R = 0.3$ jet as a function of $p_{t,\text{top}}^{\text{reco}}$.)

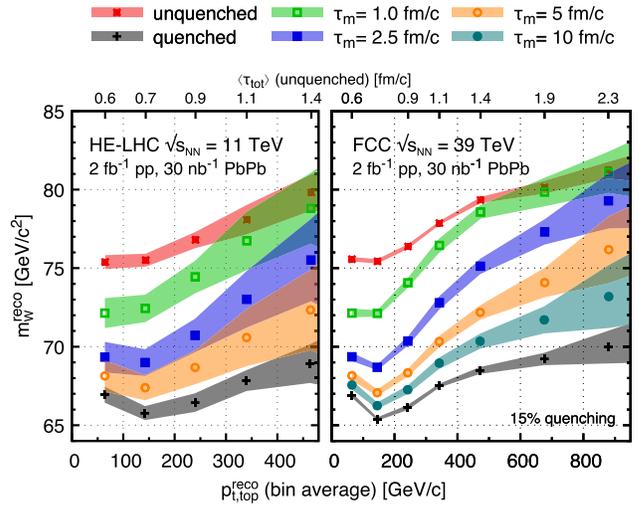


FIG. 4. Dependence of the reconstructed W mass on the reconstructed top p_t for HE-LHC (left) and FCC (right) collisions. The quenched result corresponds to baseline full modification of the pp results, which would in practice be obtained using knowledge of quenching from other measurements.

Figure 5 shows our estimate of the maximum τ_m that can be distinguished at 2 standard deviations from the baseline full quenched result, for different colliders [36,37] as a function of $\mathcal{L}_{\text{PbPb}}$. The number of standard deviations takes into account the statistical uncertainty of m_W^{fit} , for both the actual heavy-ion data and a reference sample, as well as an additional 1% systematic uncertainty (see Supplemental Material [8] and Refs. [22,38]). The reference sample is obtained using the same procedure as for the bottom bands in Figs. 3 and 4, i.e., using 2 fb^{-1} of pp events with a rescaling of particle momenta by a factor \mathcal{Q}_0 and inclusion of underlying-event fluctuations.

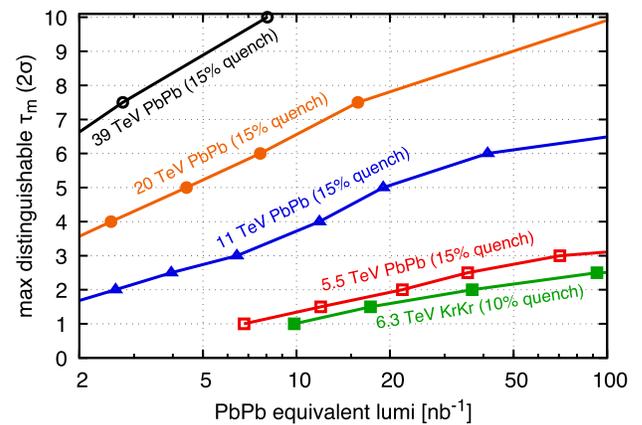


FIG. 5. The maximum medium quenching end time τ_m that can be distinguished from full quenching with 2 standard deviations, as a function of luminosity for different collider energies [36,37] and species. For the KrKr points, the $\mathcal{L}_{\text{KrKr}}$ value that is used is equal to $\mathcal{L}_{\text{PbPb}}(A_{\text{Pb}}/A_{\text{Kr}})^2$, i.e., maintaining an equal number of nucleon-nucleon collisions.

For each collider luminosity and energy the results are obtained by choosing a $p_{t,\text{top}}^{\text{reco}}$ cut so as to maximize the significance. We have verified that if we increase the fluctuations, σ_{p_t} , the required luminosity scales as $\sigma_{p_t}^2$, in line with expectations.

Lighter ions such as Kr are potentially promising, despite their smaller quenching effects [39], because of the potential for order-of-magnitude higher effective integrated nucleon-nucleon luminosities [40,41]. They are discussed further in the Supplemental Material [8].

To conclude, in this work we have shown that the study of top quarks and their decays has a unique potential to resolve the time dimension in jet-quenching studies of the QGP. To benefit from this potential requires a sufficiently large sample of top quarks, in particular to enhance event rates on the high- p_t tail, which gives the sensitivity to the longer timescales. At the LHC, with currently planned luminosity, such a program could begin. With higher energy colliders or a significantly increased luminosity at the LHC (whether from longer running or lighter ion species), there would be substantial prospects for using jet quenching to study the evolution of the QGP over the first few fm/ c . Overall, our results provide a strong motivation for a program of experimental studies of top-quark production in heavy-ion collisions.

We are grateful to John Jowett for bringing to our attention the potential for higher nucleon-nucleon luminosities with ions lighter than Pb and to Detlef Küchler for information on possible ion species in the LHC. We would also like to thank Andrea Giammanco for exchanges regarding pseudotop definitions, Phil Harris for discussions concerning the use of $W + \text{jet}$ events, and Roberto Franceschini for a comment on the manuscript. This work was supported in part by the Fundação para a Ciência e Tecnologia (Portugal) under contracts CERN/FIS-NUC/0049/2015 (L. A. and J. G. M.), Investigador FCT—Development Grant IF/00563/2012 (JGM) and SFRH/BPD/103196/2014 (L. A.); and by European Research Council Grant No. HotLHC ERC-2011-StG-279579, by Ministerio de Ciencia e Innovacion of Spain under Project No. FPA2014-58293-C2-1-P and Maria de Maetzu Unit of Excellence MDM-2016-0692, by Xunta de Galicia AGRUP2015/11 (CAS).

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