On similarity of jet quenching and charmonia suppression

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Abstract

We quantify the magnitude and the color charge dependence of the medium induced parton energy loss in lead-lead collisions at the LHC using the data on inclusive jet suppression. The extracted color charge dependence shows that the difference between the in-medium loss of quarks and gluons is consistent with the difference between the radiation of quarks and gluons in the vacuum. Then, we examine the energy loss of prompt charmonia and we point to a remarkable similarity between the quenching of light-quark-initiated jets and the prompt charmonia suppression. Finally, we discuss possible sources of this similarity.

1. Introduction

Collisions between lead nuclei at the LHC produce colored medium where relevant degrees of freedom are deconfined quarks and gluons [1]. Hard scattering interactions in perturbative quantum chromodynamics (pQCD) lead to production of two highly virtual back-to-back partons (in the leading order of pQCD) which subsequently evolve as parton showers, hadronize, and are experimentally observed as back-to-back dijet. If partons traverse on their path a colored medium they lose energy which can be seen as modification of jet yields and jet properties. This phenomenon is commonly called “jet quenching” [2–4]. The first evidence of jet quenching at the LHC was provided by the measurement of jet pairs [5, 6]. Often, the magnitude of jet quenching is quantified by the nuclear modification factor, $R_{AA}$, which is the ratio of per-event-normalized yields in lead-lead (Pb+Pb) collisions to a cross-section in proton-proton (pp) collisions scaled by the nuclear overlap function. A precise measurement of jet $R_{AA}$ was recently provided in Ref. [7]. Understanding the jet quenching means understanding the interaction of energetic color charges with the deconfined medium and the properties of this medium.

Not only jets but also charmonia can be used as tools to reveal the properties of the medium and its interactions. The production of charmonia in elementary collisions is often described in a nonrelativistic QCD effective-field-theory (EFT) framework [8]. In that theory, first, the $c\bar{c}$ pair is produced either in a color singlet or color octet state. This “pre-resonant” $c\bar{c}$ pair then binds into a physical charmonium by non-perturbative evolution described in terms of long-distance matrix elements. The pre-resonant pair in the color octet state changes its color and spin by radiating off gluon(s) when evolving to the physical quarkonium state while the pair in the color singlet state retains these quantum numbers unchanged.

In nucleus-nucleus collisions, the production of charmonia was observed to be strongly suppressed with respect to proton-proton yield at LHC, RHIC, and SPS [9]. Generally, charmonia suppression can be described using the EFT framework at finite temperature in the limit of weakly coupled medium or in the lattice-QCD in the strongly coupled regime [10]. In the EFT framework at finite temperature the thermal part of $c\bar{c}$ potential has both a real and imaginary part [11]. The real part of the $c\bar{c}$ potential is connected with color screening of the potential in the deconfined medium. The imaginary part of the potential is connected with thermal decay and it is argued that it may be a dominant mechanism for the charmonia suppression within the EFT framework [12]. Since heavy quarks are not fully thermalized in the medium, further model assumptions need to be made in order to predict charmonium production rates. Examples of these models are transport models, statistical hadronization models, collisional dissociation models, or comover models which are reviewed in Ref. [9]. Different mechanisms leading to charmonia suppression that
are implemented in these models play different role at different kinematic regions and center-of-mass energies which makes the interpretation of similarities or differences in the charmonia suppression between the LHC, RHIC, and SPS complicated.

In proton-nucleus (or deuteron-nucleus) collisions, the production of charmonia was observed to be also modified with respect to proton-proton yield although the modifications are generally smaller than those seen in nucleus-nucleus collisions [9]. These modifications are due to an interplay of various effects such as effects of nuclear modifications to parton distribution functions (shadowing, anti-shadowing, EMC effect), multiple parton scattering, or nuclear absorption of bound state. These “cold nuclear matter effects” (CNM effects) are present in nucleus-nucleus collisions as well with a strength that depends on the choice of kinematic region. Therefore, they need to be considered when interpreting the nucleus-nucleus data.

This paper elaborates on the quantification of the jet quenching and it explores a similarity in the suppression of jets and prompt charmonia (that is not coming from weak decay of $B$-hadrons) in $\sqrt{s_{\text{NN}}} = 2.76$ TeV Pb+Pb collisions at the LHC. The work is organized as follows. First, the effective suppression parameters of high-$p_T$ quarks and gluons are extracted from jet suppression measurements. Then, these parameters are used to model the suppression of prompt charmonia. The result is compared with several recent measurements. Finally, the connection between the energy loss of jets and the charmonia suppression is discussed.

2. Single jet suppression

It was shown in a recent paper on the interpretation of single jet suppression measurements at the LHC [13] that many of the features seen in the data are driven by a primordial parton spectrum and the different quark and gluon energy loss. Further, it is concluded in that study that the suppression data on jets can be described by an effective quenching model (hereafter called EQ model) in which partons lose energy depending on their initial transverse momentum, $p_{T,\text{ini}}$, and an effective color factor, $c_F$, such that the total energy lost by a parton is

$$\Delta p_T = c_F \cdot s \cdot \left(\frac{p_{T,\text{ini}}}{p_{T,0}}\right)^\alpha.$$

(1)

Here $s$ and $\alpha$ are free parameters of the model, $p_{T,\text{ini}}$ is the transverse momentum of a parton initiating a jet and $p_{T,0}$ is an arbitrary scale, here and in Ref. [13] set to 40 GeV. The parameter $c_F$ was fixed to be 1 and 9/4 for light-quark-initiated jets and gluon-initiated jets, respectively. Input to the model was the parameterization of the unquenched jet-$p_T$ spectra which was obtained from the PYTHIA8 generator [14]. The EQ model successfully described the representative data on the single jet suppression at high-$p_T$; the inclusive jet $R_{AA}$ in various rapidity intervals [7], trends in the jet fragmentation functions [15, 16] at $p_T \gtrsim 10$ GeV and the inclusive charged particle $R_{AA}$ at $p_T \gtrsim 20$ GeV [17].

The EQ model represents a model with minimal assumptions on the physics of the jet quenching process. The dynamics of the quenching process as well as the properties of the medium are encapsulated in a few free parameters. The fact that not only the inclusive jet suppression but also the jet structure is largely captured by the model speaks in favor of a physics picture in which a significant part of a parton shower remains unresolved by the medium. That may happen if the parton shower loses its energy coherently and subsequently fragments as in the vacuum. Indeed, it was recognized in several theoretical papers that such color coherence effects play an important role in the jet quenching process [18–21]. If the parton shower, or its large part, radiates as one object, one can ask if it is possible to find some similarities between the suppression of jets and a suppression of other objects with an internal structure. One such candidate are the charmonia. Before turning the attention to that question, the original model calls for an extension: the color factor should be extracted from the data and a possible dependence on the input spectra should be quantified.

The choice of $c_F = C_A/C_F = 9/4$ used in the EQ model for gluons represents an assumption on the difference in the probability to radiate a gluon from a gluon and quark source in the vacuum in the $Q \to \infty$ limit [22] or the soft limit [23]. The value of $c_F$ can be different due to both the neglected non-leading corrections [24] and the presence of the deconfined medium. Thus, a global fit has been performed to extract $s$, $\alpha$ and $c_F$ simultaneously. This has been done by minimizing the difference between the EQ model and measured jet $R_{AA}$ [7] in different rapidity intervals and centrality bins. This procedure follows the logic of extracting this factor in the vacuum [25, 26].

To test for a sensitivity of the extracted sup-
\[
s = x \cdot N_{\text{part}} + y \quad x = (12.3 \pm 1.4) \cdot 10^{-3} \text{ GeV}, \\
y = 1.5 \pm 0.2 \text{ GeV}
\]

Table 1: Parameters of the effective quenching model extracted from data. The \(\chi^2/\text{dof} = 0.63\) for \(\text{dof} = 287\). For details see the text.

| \(s = x \cdot N_{\text{part}} + y\) | \(x = (12.3 \pm 1.4) \cdot 10^{-3} \text{ GeV}, \) |
| \(y = 1.5 \pm 0.2 \text{ GeV}\) |
| \(\alpha\) | 0.52 \pm 0.02 |
| \(c_F\) | 1.78 \pm 0.12 |

Quarkonia suppression

There is no unique interpretation of the charmonia suppression measurements as of now [9]. New measurements at the LHC [33–38] should provide more insight to the mechanism of the charmonia suppression. The new precise measurements of the prompt \(J/\psi\) in the muon channel [33, 34] showed that the nuclear modification factor, \(R_{AA}^{J/\psi}\), reaches a value of \(\sim 0.2\) in the most central collisions \((N_{\text{part}} \gtrsim 350)\), continuously grows up to a value of \(\sim 0.6 – 0.7\) reached in the most peripheral collisions \((N_{\text{part}} \lesssim 50)\). The \(R_{AA}^{J/\psi}\) exhibits only a weak (if any) dependence on the \(J/\psi\) momentum in the region of \(p_T = 6.5 – 30\) GeV and \(|y| < 2.4\). The dependence of \(R_{AA}^{J/\psi}\) on the rapidity is also weak. More recently, a prompt production of \(\psi(2S)\) was also measured in terms of a double ratio of measured yields, \((N_{\psi(2S)}/N_{J/\psi})_{\text{pp}}/\langle N_{\psi(2S)}/N_{J/\psi}\rangle|_{\text{pp}} = R_{AA}^{\psi(2S)}/R_{AA}^{J/\psi}\) [37]. It was shown that \(\psi(2S)\) yields are suppressed by a factor of \(\sim 2\) with respect to \(J/\psi\) in the range \(|y| < 1.6\) and \(6.5 < p_T < 30\) GeV.

To test the idea of similarity in the physics of jet quenching and prompt charmonia suppression the EQ model described in the previous section has been employed. The input to the model are \(p_T\) spectra of \(J/\psi\) and \(\psi(2S)\) and effective parameters obtained from the analysis of jet \(R_{AA}\). The \(p_T\) spectra were obtained from PYTHIA8 (the same initial setup as in Ref. [13] was used) which was reweighted to reproduce the data measured in \(pp\) collisions at \(2.76\) TeV [39]. It was found that PYTHIA reproduces well the shape of the \(J/\psi\) \(p_T\) spectra even without reweighting, while a reweighting was needed to reproduce the \(p_T\) spectra of \(\psi(2S)\)(weights range from 0.2 to 6). The realistic \(p_T\) spectra were then used as an input to the EQ model which was run with two different settings of the color factor: first, corresponding to the color factor for the energy loss of light-quark initiated jets (defined to be one), and second, corresponding to the color factor extracted for the energy loss of gluon-initiated jets. The comparison of the data with the model is shown in Fig. 1. An excellent agreement of the model with the data for the case of the light-quark energy loss is seen. The \(N_{\text{part}}\) dependence of \(R_{AA}^{J/\psi}\); its \(p_T\) and rapidity dependence are reproduced.

The ability of the model to reproduce the suppression of \(\psi(2S)\) is shown in the Fig. 2 where the model is compared with the data on the ratio of nuclear modification factors, \(R_{AA}^{\psi(2S)}/R_{AA}^{J/\psi}\), from Ref. [37]. Remarkably, a good agreement between the model and the data is seen. The model reproduces the measurement well except for the most peripheral collisions. Here, however, no significant \(\psi(2S)\) signal was measured by CMS and consequently only a limit at 95% confidence level on the value of the ratio was provided.

The striking similarity between the measured \(J/\psi\) and \(\psi(2S)\) suppression and the energy loss of jets suggests that the radiative energy loss may
be a dominant contribution to the energy loss of charmonia in the studied kinematic region as we will discuss in the next section. Now, we will discuss impact of feed-down contributions from excited states on presented results and the role of CNM effects. The measured charmonia production generally includes direct production from the hard interaction, as well as charmonium feed-down from excited states. While the feed-down contribution from excited resonances to $\psi(2S)$ state is minimal, the feed-down contribution to $J/\psi$ is significant [9]. Thus, it is important to evaluate the impact of feed-down on presented results. The size of feed-down contribution from $\psi(2S)$ and $\chi_c$ decays to $J/\psi$ were estimated to be 8% and 25%, respectively [41]. The $p_T$ dependence of the dominant feed-down contribution of $\chi_c$ to $J/\psi$ was then evaluated in $pp$ collisions at the LHC [42, 43]. In particular, for the central rapidity region of $|y| < 0.75$, it was found that the contribution from $\chi_c$ is on average 25% varying by only 2% in the $p_T$ interval of $10 - 30$ GeV. Also measured in $pp$ collisions was the $p_T$ spectrum of $\chi_c$ [43]. To access the impact of the feed-down on presented results, the measured $\chi_c$ and $\psi(2S)$ spectra and fractions of prompt $J/\psi$ produced in $\chi_c$ and $\psi(2S)$ decays, respectively, were used to reweight the initial spectrum of $J/\psi$ such that its shape reflects a contribution from excited states. The $R_{AA}$ of $J/\psi$ was then recalculated using this new spectrum. The new reweighted spectrum characterizes a physics picture in which it is always the excited

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**Figure 1:** The $R_{J/\psi}^{AA}$ predicted by the model compared to the data measured differentially in $p_T$ of $J/\psi$ (left), rapidity of $J/\psi$ (middle), and the number of participants (right) [33, 34]. The model is evaluated in two configurations of the effective color factor – the color factor corresponding to light quarks and gluons.

**Figure 2:** The ratio of $R_{\psi(2S)}^{AA}$ to $R_{J/\psi}^{AA}$ predicted by the model compared to the data [37]. The model is evaluated in two configurations of the effective color factor – the color factor corresponding to light quarks and gluons.

**Figure 3:** The $R_{J/\psi}^{AA}$ predicted by the model compared to the data measured by ALICE at low $p_T$ in the forward rapidity region [40].
state which loses the energy in the medium while the \( J/\psi \) resulting from the decay of that excited state does not lose the energy. More realistic scenario is that only a fraction of \( \chi_c \) or \( \psi(2S) \) loses the energy while the rest first decays and then it loses the energy as \( J/\psi \). Since we do not know such a fraction, the difference of reweighted \( R_{AA} \) and original \( R_{AA} \) was used as an estimate of the uncertainty of presented results. Maximal difference between the reweighted and original \( R_{AA} \) was found to be less than 10%. This estimate is similar to the estimate of the impact of feed-down on the nuclear modification factor measured in \( p+\text{Au} \) collisions at RHIC which was found to be 5% [44].

The uncertainty in the determination of \( R_{AA} \) due to the feed-down effects was combined with the uncertainty in the determination of \( R_{AA} \) due to uncertainties in parameters of the EQ model and is plotted on Figures 1 and 2 as a shaded band.

Besides feed-down effects, the interpretation of presented results might be obscured by initial-state effects or effects from final-state nuclear interactions that are unrelated to the presence of the hot deconfined medium, i.e. by CNM effects. Sizable suppression of \( J/\psi \) was seen in proton-lead (\( p+\text{Pb} \)) collisions in the forward rapidity region or at low \( p_T \) (\( p_T \lesssim 6 \text{ GeV} \)) in the LHC [45–47] which clearly suggests that these effects come into the play. On the contrary, at high \( p_T \) (\( p_T \gtrsim 6 \text{ GeV} \)) in the midrapidity region at the LHC, the nuclear modification factor measured in \( p+\text{Pb} \) collisions is consistent with unity within the precision of measurements [39, 45]. This observation is consistent with the estimate done using EKS98 nPDFs [48] which quantifies the impact of CNM effects, namely the shadowing, on the \( R_{AA} \) to be less than 10% in the kinematic region probed in this paper [9]. While this suggests that CNM effects should not affect the interpretation of the similarity of the jet quenching and charmonia suppression, there might still be a group of CNM effects that is common for both, charmonia and jets. Suggestive of that is a sizable suppression seen in the most peripheral bin for both, the charmonia and jets.

Figures 1 and 2 represent a selection of all available LHC data on prompt \( J/\psi \) and \( \psi(2S) \) for which corresponding \( pp \) reference spectra exist which allows an exact data-to-model comparison. Besides those high-\( p_T \) \( R_{AA} \) measurements, ALICE Collaboration provided also measurement of \( R_{AA}^{J/\psi} \) [36] for which the corresponding \( pp \) spectra were measured [49]. This measurement presents \( R_{AA} \) of inclusive \( J/\psi \) (that is with no separation of non-prompt \( J/\psi \) contribution which is however smaller than 15% [50]) in the forward rapidity region and at low \( p_T \). As discussed before, in this kinematic region CNM effects play a significant role. It was also shown in past that recombination and statistical hadronization processes likely play a significant role in this kinematic region [51–54]. Thus, we cannot expect that the model presented here will reproduce the data. Nevertheless, it is instructive to quantify a departure of the model from the data. This is shown in Fig. 3. One can see that the model can reproduce the \( R_{AA}^{J/\psi} \) at \( p_T \gtrsim 6 \text{ GeV} \) where ALICE data in the forward region agrees with CMS data measured in the midrapidity region. On the contrary, a significant departure of the model from the data is seen at low \( p_T \).

4. Discussion

The ability of the EQ model to reproduce the suppression data on \( J/\psi \) and \( \psi(2S) \) suggests that the measured shape of the suppression at high-\( p_T \) is driven by the shape of the initial spectra of charmonia and that the radiative energy loss may play a dominant role at high-\( p_T \). We will leave the full analysis of this observation and the observation of similarity between the light-quark suppression and the charmonia suppression for separate works. Here, we will only summarize straightforward leading order calculations searching for a similarity between the radiation of quarks and charmonium. In particular, we discuss two basic scenarios: 1) charmonium is produced early in the collision in the color octet state and radiates coherently; 2) charmonium is produced late, from quarks or gluons that are already quenched.

For the first scenario, ratio is calculated of the probability of radiating a gluon from a charmonium in the color octet state, \( P_\psi \), to the probability of radiating a gluon from a single light quark, \( P_q \). This ratio is calculated in the collinear limit, leading to no change in the spin of charmonium due to the radiation, and under the assumption that the \( c\bar{c} \) pair is not dissociated and radiates coherently in the range of virtualities from \( Q_{\text{max}}^\psi \) to \( Q_{\text{min}}^\psi \). The result is

\[
\frac{P_\psi(Q_{\text{min}}^\psi, Q_{\text{max}}^\psi)}{P_q(Q_{\text{min}}, Q_{\text{max}})} = \frac{C_F}{C_F} \left( 1 + \ln \frac{Q_{\text{max}}}{Q_{\text{min}}} \cdot \ln^{-1} \frac{Q_{\text{max}}}{Q_{\text{min}}} \right),
\]

(2)
where $c_{\psi} = C_A$ is the color factor for the radiation from charmonium. Constant $k$ relates virtualities in the two processes, $Q^\psi = kQ$ \footnote{Equation (2) holds also for the case of massive splitting functions calculated in the quasi-collinear limit [55].}. The ratio (2) is equal to one if the virtuality range differs between the two processes (e.g. $k_{\text{max}}/k_{\text{min}} \approx 1/9$ for $Q_{\text{min}} = 0.2$ GeV and $Q_{\text{max}} = 10$ GeV). If this is the case, Eq. (2) predicts that the $R_{AA}$ of $J/\psi$ should start to deviate from the $R_{AA}$ of light-quark initiated jets at higher transverse momenta due to the slow logarithmic dependence on the virtuality. In particular, at $p_T = 50$ GeV, the $R_{AA}$ of light-quark initiated jets should be 1.3 times larger compared to the measured $R_{AA}$ of $J/\psi$. This prediction can be tested in the LHC run 2 data. Not quantified in the formula is the dead cone effect which may also decrease the resulting radiation of the charmonium [56, 57]. Another factor not accounted for in this scenario is a presence of the charmonium in the color singlet state which might however represent a small contribution compared to the color octet state [58]. Irrespective of these important details, Eq. (2) implies that a simple expectation that the radiative energy loss of gluon-initiated jets is not valid since not only the color factors enter here but also kinematic range over which the two systems radiate need to be considered.

In the second scenario, the charmonium is produced late, from quarks or gluons that are already quenched. While the correlation between the $p_T$ of the initial parton and the $p_T$ of charmonium is rather strong, less steep spectra of charmonia than the $R_{AA}$ of partons. It was explicitly checked by modeling using PYTHIA. In this scenario, the similarity between the suppression of jets and prompt charmonia would be accidental, steaming from an intriguing combination of quark and gluon energy loss which disfavors this scenario.

5. Summary

This paper has presented a quantification of the jet quenching in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions which is based on an extension of the effective quenching model [13]. In particular, extracted from the data was the effective color factor, $c_F$, characterizing a difference in the probability to radiate a gluon from a gluon and quark source. The extracted value, $c_F = 1.78 \pm 0.12$, is consistent with the value obtained for vacuum [24, 25]. Using the quantification of the energy loss of jets, a similarity between the suppression of jets and prompt charmonia was explored. A striking similarity between the measured $J/\psi$ and $\psi(2S)$ suppression and the energy loss of light-quark initiated jets was seen. While this observation requires a thorough theoretical analysis, it suggests that the radiative energy loss may be a dominant contribution to the charmonia suppression at $p_T \gtrsim 6$ GeV at the LHC. Quantification of the magnitude of the jet quenching together with observations made in this paper should improve the understanding of physics mechanism behind both, the jet quenching and charmonia suppression. They may also contribute to better understanding of general aspects of charmonia formation.

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References

[1] F. Karsch, E. Laermann, Thermodynamics and in medium hadron properties from lattice QCDarXiv: hep-lat/0305025.
[2] U. A. Wiedemann, Jet Quenching in Heavy Ion Collisions (2010) 521–562[Landolt-Bornstein23,521(2010)]. arXiv:0908.2306, doi:10.1007/978-3-642-01539-7_17.
[3] A. Majumder, M. Van Leeuwen, The Theory and Phenomenology of Perturbative QCD Based Jet Quenching, Prog. Part. Nucl. Phys. A66 (2011) 41–92. arXiv:1002.2206, doi:10.1016/j.ppnp.2010.09.001.
[4] Y. Mehtar-Tani, J. G. Milhano, K. Tywoniuk, Jet physics in heavy-ion collisions, Int. J. Mod. Phys. A28 (2013) 1340013. arXiv:1302.2579, doi:10.1142/S0217751X13400137.
[5] ATLAS Collaboration, Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.77$ TeV with the ATLAS Detector at the LHC, Phys. Rev. Lett. 105 (2010) 252303. arXiv:1011.6182, doi:10.1103/PhysRevLett.105.252303.
[6] CMS Collaboration, Observation and studies of jet quenching in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV, Phys. Rev. C84 (2011) 024906. arXiv:1102.1957, doi:10.1103/PhysRevC.84.024906.
[7] ATLAS Collaboration, Measurements of the Nuclear Modification Factor for Jets in Pb+Pb Collisions at \(\sqrt{s_{\text{NN}}} = 2.76\) TeV with the ATLAS Detector, Phys.Rev.Lett. 114 (7) (2015) 072002. arXiv:1411.2357, doi:10.1103/PhysRevLett.114.072002.

[8] G. T. Bodwin, E. Braaten, G. P. Lepage, Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium, Phys. Rev. D51 (1995) 1125–1171, [Erratum: Phys. Rev.D55,5853(1997)]. arXiv: hep-ph/9407339, doi:10.1103/PhysRevD.55.5853, 10.1103/PhysRevD.51.1125.

[9] A. Andronic, et al., Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions, Eur. Phys. J. C76 (3) (2016) 107. arXiv:1506.03981, doi:10.1140/epjc/s10052-016-3896-0.

[10] N. Brambilla, et al., Heavy quarkonium physics arXiv: hep-ph/0412158.

[11] N. Brambilla, G. Ghiglieri, A. Vairo, P. Petreczky, Static CMS Collaboration, Measurement of jet fragmentation, Eur. Phys. J. C76 (3) (2016) 109. arXiv:1506.03981, doi:10.1140/epjc/s10052-016-3819-5.

[12] N. Brambilla, et al., Heavy quarkonium physics arXiv: hep-ph/0412158.

[13] T. Sjostrand, S. Ask, J. R. Christiansen, R. Corke, J.-P. Blaizot, E. Iancu, Y. Mehtar-Tani, Medium-effects in jet production in PbPb and pp collisions at \(\sqrt{s} = 2.76\) TeV, Phys.Rev.Lett. B739 (2014) 320–342. arXiv:1406.2979, doi:10.1103/PhysRevLett.94.171802.

[14] K. Konishi, A. Ukawa, G. Veneziano, Jet Calculus: A Simple Algorithm for Resolving QCD Jets, Nucl. Phys. B157 (1979) 45–107. doi:10.1016/0550-3213(79)90053-1.

[15] V. A. Khoze, S. Lupia, W. Ochs, Perturbative universality in soft particle production, Eur. Phys. J. C5 (1998) 77–90. arXiv:hep-ph/9711392, doi:10.1017/s005291800000249.

[16] A. Capella, I. M. Dremin, J. W. Gary, V. A. Nemitailo, J. Tran Thanh Van, Evolution of average multiplicities of quark and gluon jets, Phys. Rev. D61 (2000) 074009. arXiv:hep-ph/9910226, doi:10.1103/PhysRevD.61.074009.

[17] D. Acosta, et al., Measurement of charged particle multiplicities in gluon and quark jets in pp collisions at \(\sqrt{s} = 1.8\) TeV, Phys. Rev. Lett. 94 (2005) 171802. doi:10.1103/PhysRevLett.94.171802.

[18] G. Abbiendi, et al., Experimental properties of gluon and quark jets from a point source, Eur. Phys. J. C11 (1999) 217–238. arXiv:hep-ex/9903027, doi:10.1016/s0168-9268(00)00568-2.

[19] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, JHEP 06 (2010) 043. arXiv:1002.2581, doi:10.1007/JHEP06(2010)043.

[20] S. Alioli, K. Hamilton, P. Nason, C. Oleari, E. Re, Jet pair production in POWHEG, JHEP 04 (2011) 081. arXiv:1012.3390, doi:10.1007/JHEP04(2011)081.

[21] A. D. Martin, W. J. Stirling, R. S. Thorne, G. Watt, Parton distributions for the LHC, Eur. Phys. J. C63 (2010) 189–285. arXiv:0901.0002, doi:10.1140/epjc/s10052-009-1072-5.

[22] R. D. Ball, L. Del Debbio, S. Forte, A. Guffanti, J. I. Latorre, J. Rojo, M. Ubiali, A first unbiased global NLO determination of parton distributions and their uncertainties, Nucl. Phys. B838 (2010) 136–206. arXiv:1005.4607, doi:10.1016/j.nuclphysb.2010.05.008.

[23] CMS Collaboration, Measurement of the Inclusive Jet Production in PbPb and pp collisions at \(\sqrt{s} = 2.76\) TeV, Phys.Rev.Lett. 107 (2011) 252001. arXiv:1106.0208, doi:10.1103/PhysRevLett.107.252001.

[24] CMS Collaboration, Centrality, rapidity and transverse momentum dependence of \(J/\psi\) suppression in PbPb collisions at \(\sqrt{s_{\text{NN}}} = 2.76\) TeV, Phys. Lett. B764 (2017) 342–353. arXiv:1610.05479, doi:10.1016/j.physletb.2017.05.046.

[25] CMS Collaboration, J/\(\psi\) results from CMS in PbPb Collisions at \(\sqrt{s_{\text{NN}}} = 2.76\) TeV, Phys. Lett. B734 (2014) 320–342. arXiv:1401.2855, doi:10.1016/j.physletb.2014.05.064.

[26] CMS Collaboration, Measurement of Prompt \(J/\psi\), prompt \(J/\psi\), and \(Y(1S)\) in PbPb collisions at \(\sqrt{s_{\text{NN}}} = 2.76\) TeV, Phys. Lett. B764 (2017) 342–353. arXiv:1610.05479, doi:10.1016/j.physletb.2017.05.046.

[27] CMS Collaboration, Suppression of non-prompt \(J/\psi\), prompt \(J/\psi\), and \(Y(1S)\) in PbPb collisions at \(\sqrt{s_{\text{NN}}} = 2.76\) TeV, JHEP 05 (2012) 063. arXiv:1201.5069, doi:10.1007/JHEP05(2012)063.

[28] CMS Collaboration, J/\(\psi\) results from CMS in PbPb collisions, with 150mub-1 data, CMS-PAS-HIN-12-014.
113.262301.

[38] ALICE Collaboration, Inclusive, prompt and non-prompt $J/\psi$ production at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, JHEP 07 (2015) 051. arXiv:1504.07151, doi:10.1007/JHEP07(2015)051.

[39] ATLAS Collaboration, Study of $J/\psi$ and $\psi(2S)$ production in $\sqrt{s_{NN}} = 5.02$ TeV $p + p$ and $\sqrt{s} = 2.76$ TeV $pp$ collisions with the ATLAS detector, ATLAS-CONF-2015-023.

[40] ALICE Collaboration, $J/\psi$ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 7$ TeV, Phys. Rev. Lett. 109 (2012) 072301. arXiv:1202.1383, doi:10.1103/PhysRevLett.109.072301.

[41] P. Faccioli, C. Lourenco, J. Seixas, H. K. Woehri, Study of $\psi'$ and $\chi_c$ decays as feed-down sources of $J/\psi$ hadroproduction, JHEP 10 (2008) 004. arXiv:0809.2153, doi:10.1088/1126-6708/2008/10/004.

[42] R. Adare, et al., Measurement of the ratio of prompt $\chi_c$ to $J/\psi$ production in $pp$ collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B718 (2012) 431-440. doi:10.1016/j.physletb.2012.10.068.

[43] ATLAS Collaboration, Measurement of $\chi_{c1}$ and $\chi_{c2}$ production with $\sqrt{s}=7$ TeV $pp$ collisions at ATLAS, JHEP 07 (2014) 154. arXiv:1404.7035, doi:10.1007/JHEP07(2014)154.

[44] A. Adare, et al., Nuclear Modification of $\psi'$, $\chi_c$, and $J/\psi$ Production in d+Au Collisions at $\sqrt{s_{NN}}=200$ GeV, Phys. Rev. Lett. 111 (20) (2013) 202301. arXiv:1305.5516, doi:10.1103/PhysRevLett.111.202301.

[45] ALICE Collaboration, Rapidity and transverse-momentum dependence of the inclusive $J/\psi$ nuclear modification factor in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, JHEP 06 (2015) 055. arXiv:1503.07179, doi:10.1007/JHEP06(2015)055.

[46] ALICE Collaboration, $J/\psi$ production and nuclear effects in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, JHEP 02 (2014) 073. arXiv:1308.6726, doi:10.1007/JHEP02(2014)073.

[47] R. Aaij, et al., Study of $J/\psi$ production and cold nuclear matter effects in p-Pb collisions at $\sqrt{s_{NN}} = 5$ TeV, JHEP 02 (2014) 072. arXiv:1308.6729, doi:10.1007/JHEP02(2014)072.

[48] K. J. Eskola, V. J. Kolhinen, C. A. Salgado, The Scale dependent nuclear effects in parton distributions for practical applications, Eur. Phys. J. C9 (1999) 61–68. hep-ph/9807297, doi:10.1007/s100520050513, 10.1007/s100529900005.

[49] ALICE Collaboration, Inclusive $J/\psi$ production in pp collisions at $\sqrt{s} = 2.76$ TeV, Phys. Lett. B718 (2012) 295–306. [Erratum: Phys. Lett.B748,472(2015)]. arXiv:1203.3641, doi:10.1016/j.physletb.2012.10.078, 10.1016/j.physletb.2015.06.058.

[50] J. Book, $J/\psi$ production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Nucl. Phys. A911 (2014) 591–595. doi:10.1016/j.nuclphysa.2014.09.082.

[51] X. Zhao, R. Rapp, Medium Modifications and Production of Charmonia at LHC, Nucl. Phys. A859 (2011) 114–125. arXiv:1102.2194, doi:10.1016/j.nuclphysa.2011.05.001.

[52] Y.-p. Liu, Z. Qu, N. Xu, P.-j. Zhuang, $J/\psi$ Transverse Momentum Distribution in High Energy Nuclear Collisions at RHIC, Phys. Lett. B678 (2009) 72–76. arXiv:0901.2757, doi:10.1016/j.physletb.2009.06.006.

[53] E. G. Ferreiro, Charmonium dissociation and recombination at LHC: Revisiting comovers, Phys. Lett. B731 (2014) 57–63. arXiv:1210.3209, doi:10.1016/j.physletb.2014.02.011.

[54] A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, The thermal model on the verge of the ultimate test: particle production in Pb-Pb collisions at the LHC, J. Phys. G38 (2011) 124081. arXiv:1106.6321, doi:10.1088/0954-3899/38/12/124081.

[55] S. Catani, S. Dittmaier, Z. Trocsanyi, One loop singular behavior of QCD and SUSY QCD amplitudes with massive partons, Phys. Lett. B500 (2001) 149–160. arXiv:hep-ph/0011222, doi:10.1016/S0370-2693(01)00065-X.

[56] Y. L. Dokshitzer, D. E. Kharzeev, Heavy quark colorimetry of QCD matter, Phys. Lett. B519 (2001) 199–206. arXiv:hep-ph/0106202, doi:10.1016/S0370-2693(01)01130-3.

[57] N. Armesto, C. A. Salgado, U. A. Wiedemann, Medium induced gluon radiation off massive quarks fills the dead cone, Phys. Rev. D69 (2004) 114003. arXiv:hep-ph/0312106, doi:10.1103/PhysRevD.69.114003.

[58] S. F. Baranov, A. V. Lipatov, N. P. Zotov, Prompt charmonia production and polarization at LHC in the NRQCD with $k_T$-factorization. Part I: $\psi(2S)$ meson, Eur. Phys. J. C75 (9) (2015) 455. arXiv:1508.05480, doi:10.1140/epjc/s10052-015-3689-x.