NLO analysis of inclusive jet, tagged jet and di-jet production in Pb+Pb collisions at the LHC

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Abstract. We present results and predictions at next-to-leading order for the recent LHC lead-lead run at a center-of-mass energy of 2.76 TeV per nucleon-nucleon pair. Specifically, we focus on the suppression the single and double inclusive jet cross sections and demonstrate how the di-jet asymmetry, recently measured by ATLAS and CMS, can be extracted from this general result. The case of jets tagged by an electroweak boson is exemplified by the $Z^0$+jet channel. We predict a signature transition from enhancement to suppression of the tagged jet related to the medium-induced modification of the parton shower. Finally, we clarify the relation between the suppression of inclusive jets, tagged jets and di-jets and the quenching of inclusive particles on the example of the recent ALICE charged hadron attenuation data.

1. Introduction

Jets physics is a new area of active research at RHIC and at the LHC that paves the way for novel tests of QCD multi-parton dynamics in heavy-ion reactions [1]. At present, perturbative QCD calculations of hard probes in elementary nucleon-nucleon reactions can be consistently combined with the effects of the nuclear medium up to next-to-leading order [2]. While such accuracy is desirable for leading particle tomography, it is absolutely essential for the new jet observables. With this motivation, we present results and predictions at NLO for the recent LHC lead-lead run at a center-of-mass energy of 2.76 TeV per nucleon-nucleon pair [3]. Our analysis includes not only final-state inelastic parton interactions in the QGP, but also initial-state cold nuclear matter effects and non-perturbative hadronization corrections.

2. Jets production and attenuation in heavy ion reactions

The basis for the evaluation of multi-jet cross sections in heavy ion collisions are the corresponding cross sections in the more elementary nucleon-nucleon reactions. Accurate perturbative calculations at next-to-leading order are essential to capture the cross section dependence of the jet radius $R = \sqrt{\delta \eta^2 + \delta \phi^2}$ [2] and provide an accurate estimate of the transverse energy $E_T$ dependence of tagged jets [4] and di-jets [5]. For inclusive jets and di-jets we use the EKS NLO results [6] and obtain baseline cross sections in excellent agreement with experiment from RHIC to LHC energies. For $Z^0$-tagged jets we use the MCFM code that works very well at the Tevatron and at the LHC [7].

2.1. Quenching of inclusive jets

In Ref. [8] it was shown that in QCD the final-state process-dependent medium-induced radiative corrections factorize in the production cross sections on the example
We find that cold nuclear matter effects [10, 11] are small and the and including the relevant tree level processes we evaluate the inclusive

R modification for jets of radius $R$ can be studied [4]. The right panel of Figure 2 shows the predicted QGP-induced quenching [5].

Collisional interactions of the in-medium parton shower can re-distribute a fraction of the jet energy to the non-Abelian plasma away from the jet axis [12]. This is simulated in the right panel of Figure 1 by a parameter $p_T^{\text{min}} = 20$ GeV. The main result is that such diffusion eliminates any residual radius dependence of the inclusive jet quenching [5].

2.2. $Z^0$-tagged jets

$Z^0$-tagged jets have been proposed as one of the important new channels that open up at the LHC to study parton energy loss and jet quenching. To utilize its potential, NLO calculations are necessary [7]. The left panel of Figure 2 shows that at tree level the jet $p_T^{\text{jet}}$ coincides with the momentum of the $Z^0$, here measured via its di-lepton decay channel. $O(G_F^2\alpha_s^2)$ is the first non-trivial order at which $Z^0$-tagged jets can be studied [4]. The right panel of Figure 2 shows the predicted QGP-induced modification for jets of radius $R = 0.2$ associated with a $Z^0$ tag in central Pb+Pb collisions. The insert shows a characteristic transition from suppression ($I_{AA} < 1$) for $p_T^{\text{jet}} > p_T^{Z0}$ to strong enhancement ($I_{AA} >> 1$) for $p_T^{\text{jet}} < p_T^{Z0}$. Integrating out the jet and including the relevant tree level processes we evaluate the inclusive $Z^0$ production cross section. We find that cold nuclear matter effects [10] [11] are small and the

Figure 1. Left panel: predicted suppression of single inclusive jets in central Pb+Pb collisions at the LHC for two different radii $R = 0.2, 0.6$ and three couplings between the jet and the medium $g_{\text{mod}} = 1.8, 2, 2.2$. Preliminary ATLAS data for $R = 0.2, 0.4$ is also shown. Right panel: jet radius dependence of the inclusive quenching factor with ($p_T^{\text{min}} = 20$ GeV) and without ($p_T^{\text{min}} = 0$ GeV) diffusion of the parton shower energy due to collisional processes.
calculation accurately predicts the $Z^0$ cross section measured in Pb+Pb collisions measured by CMS [13].

2.3. Di-jets and their $E_T$ asymmetry

New insights into the medium modification of parton showers are provided by the 2D attenuation pattern of di-jets. A specific subset of di-jets in the general $(E_T^1, E_T^2)$ plane are the ones of fixed energy asymmetry $A_J = (E_T^1 - E_T^2)/(E_T^1 + E_T^2)$. We have verified that NLO calculations of di-jets reproduce with excellent accuracy the baseline asymmetry measured in p+p collisions by the ATLAS experiment. The left panel of Figure 3 shows the first calculation for the suppression of di-jets $R_{2-jet}^{AA}$ in central Pb+Pb reactions at the LHC [5]. It is characterized by a broad region of approximately constant suppression around $E_T^1 = E_T^2$ and strong enhancement for $E_T^1 \ll E_T^2$, $E_T^1 \gg E_T^2$. The corresponding QGP-enhanced asymmetry is shown in the the right panel of Figure 3 for jet radii $R = 0.2, 0.4, 0.6$. We find that radiative energy loss [9] (green lines) can explain approximately 1/2 of the measured $A_J$ broadening [14, 15]. Diffusion of the parton shower energy away from the jet axis through collisional processes [12] eliminates the residual jet radius dependence and the theoretical calculation is compatible with the experimental measurements for all $R$.

3. Leading particle suppression

The quenching of jets and hadrons has to be understood in the same theoretical formalism. Specifically, the nuclear modification of jets for small radii approximates the suppression of leading particles [1]. An example of an early theoretical prediction [16] is given in the left panel of Figure 4 and compared to ALICE data on charged hadron attenuation in central Pb+Pb collisions [17]. The contribution of the medium-induced bremsstrahlung to hadron production below $p_T = 6$ GeV is significant and is reflected in the non-trivial and non-monotonic $p_T$ dependence of $R_{AA}(p_T)$, confirmed by experiment. Cold nuclear matter effects also play a role in this intermediate $p_T$ region. Further constraints on the mechanisms of jet quenching can
be obtained by investigating open heavy flavor production [18]. Preliminary results are already available at the LHC [19]. It will be important and illuminating in the future to extend these measurements to photon-tagged heavy meson production. Theoretical predictions for the differences in the effective fragmentation functions between light and heavy flavor $D(z_T)$ and the nuclear modification factor $I_{AA}(z_T)$ are presented in the right panel of Figure 4.

4. Summary

We presented NLO results and predictions for inclusive jet, $Z^0$-tagged jet, and di-jet production in heavy ion collisions at the LHC. We also demonstrated the relation between the quenching of jets, the attenuation of leading particles, and the modification of photon-tagged light and heavy hadron distributions. We found that in all cases there is a good qualitative understanding of the suppression of hard probes in Pb+Pb collisions at the LHC. Experimental results have already provided guidance on the directions where further theoretical developments are desirable for improved quantitative description of heavy ion reactions at the high energy frontier. Namely, these are the interaction between the parton showers and the medium and the energy loss mechanisms for heavy quarks.

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![Graph showing pT distribution for Pb+Pb collisions at the LHC]

Figure 4. Left panel: comparison of predictions for inclusive pion quenching with (solid lines) and without (dashed lines) gluon feedback to recent ALICE data in central Pb+Pb reactions at the LHC. Right panel: predicted effective fragmentation functions in photon-triggered light and heavy hadron production in central Pb+Pb reactions at the LHC. We also show the difference in the nuclear modification $I_{AA}$ for light and heavy flavor, to be tested in the future.

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