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Jet Physics at the LHC

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Abstract. The production and propagation of high p_{T} probes can explore the mechanisms of parton energy loss, deconfinement in the medium, and shed light on the relevant physical mechanisms and the microscopic properties of the medium formed in the heavy-ion collisions. In particular, partonic energy loss results in significant modification of jet spectra. The LHC opened a new era in heavy-ion physics bringing, among several, the hard probes to unreached region of the phase-space. Some of the jet physics results are discussed.

High energy partons interact with the medium and loose energy, primarily through induced gluon radiation and, to a smaller extent, elastic scattering [1]. The theory of parton energy loss in hot matter has come a long way from the "jet quenching" predictions by Bjorken and others [2] describing radiative energy loss by a fast parton.

Experimentally, several methods are used to address such questions, generally through comparison of the relative production of single particles suppression at RHIC to fully reconstructed jets at the LHC in nuclear collisions to expectations from a superposition of independent nucleon-nucleon collisions.

The thermal scale, set by the medium temperature, is very important for the parton energy loss. More specifically, the coupling between partons and medium at large scales, of the order of the initial parton energy, may be weak, governed by perturbative dynamics, and factorize from the medium. At lower scales of the order of 1 GeV, the coupling between the jet and the medium may be strong. Jet reconstruction and measurements of the jet properties aim to quantify the in-medium jet energy loss and capture the dynamics of jet quenching. At low particle momenta, the underlying event, even if considered as a background contribution to the hard probes because uncorrelated to the hard parton scattering, is an important element of the hadronic environment consisting of complex contributions, spanning over nonperturbative and perturbative QCD and including sensitivities to multiscale and low x physics. Jet reconstruction in heavy-ion collisions proceed against this large background, resulting very challenging. Dedicated algorithms and background subtraction techniques have been developed and optimized to reconstruct the collimated spray of particles associated with the original parton and contained in the jet cone radius fixed by the specific algorithm [4, 5].

At the LHC, fully reconstructed jets are available over a wide p_{T} range at $\sqrt{s_{NN}} = 2.76$ TeV confirming and extending the suppression pattern already observed for charged particles both at these energies and at lower collision energies (i.e. RHIC). However, although the original parton energy is better reconstructed in a jet than by tagging only a fast hadron, the single inclusive jet suppression is similar to that of single hadrons. This can be understood if parton energy loss is predominantly through radiation outside the jet cone radius used in the jet reconstruction algorithm.

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To quantify suppression effects, one of the most effective observable is the nuclear modification factor (R_{AA}), defined as the ratio of yields in $Nucleus - Nucleus$ collisions to those in $proton - proton$, scaled by the number of binary collisions. The ALICE R_{AA} results, imposing a minimum fragmentation bias on single tracks of 0.150 GeV/c, cover low p_{T} down to $\approx 30 - 40$ GeV/c [6] and both the CMS and ATLAS measurements [7, 8] up to $p_{\mathrm{T}} \approx 270$ GeV/c showing a relatively good agreement in the overlapping p_{T} region. Besides, a clear centrality dependence is observed. ALICE, exploring the low p_{T} region (30–110 GeV/c) finds $R_{AA} \sim 0.4$ for a jet cone radius $R = 0.3$, while ATLAS and CMS, in the high p_{T} region, find $R_{AA} = 0.5$, almost independent of jet p_{T} implying that the full jet energy cannot be captured for $R < 0.3$ in $Pb + Pb$ collisions.

A measurement of the variation of the jet yield as a function of the distance traversed through the matter can provide a direct constraint on the relative theoretical models and their estimation of the path-length dependence of energy loss. ATLAS showed reduction of 10%–20% in the jet yields as a function of $\Delta\phi$ (azimuthal separation with respect to the event plane), and in particular between $in - plane$ and $out - of - plane$ directions, at different centralities, for $60 < p_{\mathrm{T}} < 80$ GeV/c for fully reconstructed jets highlighting a strong jet suppression in the direction where the parton traverses the greatest amount of hot medium [9].

It must be noted that inclusive jet measurements provide only limited information because the initial jet energy is unknown. It has been demonstrated that the electroweak gauge bosons, which do not carry color charge, are unaffected by the medium and therefore retain the kinematics of the initial hard scattering. As a consequence, a way to understand the magnitude of the energy lost by jets is to study the boson-jet correlations, assuming that the boson momentum represents the initial jet (parton) momentum. ATLAS measurements show the mean fractional energy distribution carried by the jet opposite a photon, $x_{\mathrm{J}\gamma}$, in $Pb + Pb$ collisions [10] compared to PYTHIA simulations embedded into simulated background heavy-ion events. As the centrality increases, the distribution shifts toward smaller $x_{\mathrm{J}\gamma}$, suggesting that more and more of the jet momentum distribution falls below a minimum $x_{\mathrm{J}\gamma}$. In contrast, the PYTHIA ratio of the “true jet” to “true photon” distribution exhibits no centrality dependence. Similar results are obtained from CMS [11].

Among the fundamental measurements to be performed, one of the most important is the jet structure in the medium, meaning the longitudinal and transverse structure. The first has been done through the fragmentation functions and dijet transverse momentum imbalance. As shown in [12–14], there is a softening of the fragmentation function in the most central collisions if low momenta particles (p_{T} >1 GeV/c) are included, even if the longitudinal structure of the jet does not change in the high p_{T} >100 GeV/c region. To access to the transverse structure, the shift of the transverse momentum imbalance of the leading jet and its recoil partner has been measured. A significant shift has been found if the $Pb + Pb$ spectra is compared to the $proton - proton$ one [15]. Implications for the energy loss mechanism must be extracted by models.

The Quark Gluon Plasma is expected to modify the jet shape both because of parton interactions with the medium and because soft particle production in the underlying event adds more particles to the jet. Thus, the energy flow inside a jet, sensitive to the characteristics of the medium traversed by the probe, can be studied through jet shape analysis which should then widen due to quenching effects. CMS has measured the average fraction of the jet transverse momentum within annular regions of ΔR=0.05 from the inner part of the jet to the edge of the jet cone. Correcting for the underlying events and all instrumental effects in central collisions, moderate jet broadening in the medium is observed for $R = 0.3$ [16]. The effect increases for more central collisions. This is consistent with the concept that energy lost by jets is redistributed at large distances from the jet axis, outside the jet cone. For an update on theoretical developments at high p_{T}, see Ref. [17].

As discussed previously, a key issue is the interplay between soft (flow) and hard processes (jets). This has been investigated by ALICE looking at the modification of the particle composition in jet-like structures by studying the p/π ratio in $\Delta\eta$ - $\Delta\phi$ space relative to a trigger particle. Interesting results show that, in the region of the "near-side" peak, the ratio is consistent with expectations from proton-proton collisions, estimated using PYTHIA while, in the "bulk" region, the ratio is compatible with that obtained for non-triggered events. In conclusion, there is no significant medium-induced modification of particle ratios within jets and the enhancement of the inclusive p/π ratio observed in minimum bias $Pb + Pb$ collisions is a result of bulk processes and not jet fragmentation [18].

Additional insight into the energy loss process has come from heavy flavours [19–24] and $p - Pb$ collisions [25–32], non discussed here.

Outstanding results have been achieved by using jets unveiling the properties of the hot and dense medium produced in the heavy ion collisions. Jets at the LHC, due to the larger cross section for hard processes, if compared to previous experiments, put constraints on the amount of energy loss in the medium, on its dependence on the parton type, disfavoring some available models. However, the correlation between hard (jet) and soft particles in the underlying event remains difficult to describe by any currently-known mechanisms, even if it is potentially factorizable in QCD. Deeper studies of the energy redistribution within a jet or of the low p_{T} particles emitted far away from the jet axis, together with the precise description and modeling of the modification of the jet fragmentation function and jet shape, will shed light on new interesting phenomena that arise as a consequence of the interesting nature of jets.

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