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Nuclear Physics A 931 (2014) 165–175

NUCLEAR PHYSICS A

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Theory of jet quenching in ultra-relativistic nuclear collisions

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Received 1 August 2014; received in revised form 31 August 2014; accepted 2 September 2014

Abstract

We present a short overview of recent progress in the theory of jet quenching in ultra-relativistic nuclear collisions, including phenomenological studies of jet quenching at RHIC and the LHC, development in NLO perburbative QCD calculation of jet broadening and energy loss, full jet evolution and modification, medium response to jet transport, and lattice QCD and AdS/CFT studies of jet quenching.

Keywords: Relativistic nuclear collisions; Quark–gluon plasma; Jet quenching

1. Introduction

One of the main goals of ultra-relativistic nuclear collisions, such as those performed at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC), is to create a novel state of matter, called quark–gluon plasma (QGP), and study its various properties. Large transverse momentum quarks and gluons, produced from early stage hard scatterings, have been regarded as very useful probes of such highly excited nuclear matter. These hard partonic jets interact with medium constituents during their propagation through the QGP medium before fragmenting into hadrons. The interaction with the medium usually causes partons to lose energy, therefore observables associated with jets are modified as compared to the vacuum jets such as the case in elementary nucleon–nucleon collisions.

The basic framework for studying jet production in ultra-relativistic nuclear collisions is the perturbative QCD factorization paradigm, i.e., processes involving large transverse momentum

http://dx.doi.org/10.1016/j.nuclphysa.2014.09.004

(p_T) transfer may be factorized into long-distance and short-distance pieces. For example, the cross section of single inclusive high p_T hadron production in elementary nucleon–nucleon collisions may be obtained as follows:

$$d\sigma_h \approx \sum_{abjd} f(x_a) \otimes f(x_b) \otimes d\sigma_{ab\to jd} \otimes D_{j\to h}(z_j). \tag{1}$$

In the above factorized formula, $f(x_a)$, $f(x_b)$ are parton distribution functions (PDF) and $D(z_j)$ denotes the fragmentation function (FF). These non-perturbative long-distance quantities are universal and usually obtained from global fitting to various experimental measurements, such as e^+e^- and deep-inelastic scattering (DIS) experiments, etc. The partonic scattering cross sections $d\sigma_{ab\to jd}$ are short-distance quantities involving large p_T transfer, and thus may be calculated using perturbative QCD techniques.

In phenomenological studies of jet energy loss and jet quenching in ultra-relativistic heavy-ion collisions, the above formula needs some modification due to the presence of the hot and dense QGP:

$$d\tilde{\sigma}_h \approx \sum_{abjj'd} f(x_a) \otimes f(x_b) \otimes d\sigma_{ab\to jd} \otimes P_{j\to j'} \otimes D_{j'\to h}\big(z'_j\big). \tag{2}$$

The additional piece $P_{j\to j'}$ is to take into account the interaction between the hard partons j and the QGP medium before fragmenting into high p_T hadrons. Often one combines the parton–medium interaction function $P_{j\to j'}$ and the vacuum FF to define the so-called medium-modified FF $\tilde{D}_{j\to h} \approx \sum_{j'} P_{j\to j'} \otimes D_{j'\to h}$; one may also define the medium-modified parton cross section by combining the parton–medium interaction with the vacuum cross section. Although the above factorized formula has been widely used in phenomenological studies of jet modification and energy loss, no formal proof of factorization is available yet for ultra-relativistic heavy-ion collisions.

2. Radiative and collisional jet energy loss

In the study of jet quenching in ultra-relativistic heavy-ion collisions, two different medium-induced mechanisms are usually considered for jet energy loss: elastic collisions with medium constituents and induced bremsstrahlung processes. The energy loss occurring in binary elastic collisions is usually referred to as collisional jet energy loss. Scatterings between hard partonic jets with medium constituents usually induce additional radiation which carries away part of the parent parton's energy; such mechanism is called radiative energy loss.

During last the decades, much effort has been focused on studying radiative jet energy loss. A number of approaches have been developed in the literature. Based on the assumptions made in different formalisms when calculating the single gluon emission spectrum, they may be cast into two categories: multiple soft scatterings, such as Baier–Dokshitzer–Mueller–Peigne–Schiff–Zakharov (BDMPS–Z), [1,2], Amesto–Salgado–Wiedemann (ASW) [3] and Arnold–Moore–Yaffe (AMY) [4] formalisms, versus few hard scatterings, such as Gyulassy–Levai–Vitev (GLV) [5] and higher twist (HT) [6] formalisms. Recently, various improvements have been done to the original jet energy loss formalisms. For example, the AMY formalism has been developed to include the finite medium length effect [7]. The GLV formalism has been extended to finite dynamical medium, and recently the effect of non-zero magnetic mass was also included [8,9]. The HT formalism has been extended to incorporate multiple scatterings [10].