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Nuclear Physics A 931 (2014) 206–215

NUCLEAR PHYSICS A

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Theoretical aspects of photon production in high energy nuclear collisions

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Received 31 July 2014; accepted 22 August 2014

Available online 6 September 2014

Abstract

A brief overview of the calculation of photon and dilepton production rates in a deconfined quark–gluon plasma is presented. We review leading order rates as well as recent NLO determinations and non-equilibrium corrections. Furthermore, the difficulties in a non-perturbative lattice determination are summarized.

Keywords: Photons; Dileptons; Hard Probes; Quark–Gluon Plasma; High order calculations

1. Introduction

Photons and dileptons have long been considered a key hard probe of the medium produced in high energy heavy-ion collisions. A chief advantage is that their coupling to the plasma is weak, which means that reinteractions (absorption, rescattering) of electromagnetic probes are expected to be negligible. These probes hence carry direct information about their formation process to the detectors, unmodified by hadronization or other late time physics.

Experimentally, there are now detailed data on both real photon and dilepton production alike at RHIC and the LHC. An overview of experimental data was presented at this conference in [1]. Photons and dileptons arising from meson decays following hadronization are subtracted from the data experimentally or form part of the "cocktail"; theoretically one then needs to deal with several sources during the evolution of the fireball: *"prompt"* photons and dileptons, produced in the scattering of partons in the colliding nuclei, *jet photons*, arising from the interactions and fragmentations of jets, *thermal* photons and dileptons, produced by interactions of the (nearly)

http://dx.doi.org/10.1016/j.nuclphysa.2014.08.070

thermal constituents of the plasma and *hadron gas* photons and dileptons, produced in later stages. Phenomenologically, one then needs to convolute *microscopic production rates* over the *macroscopic spacetime evolution* of the medium produced in the collision, which is governed by an effective hydrodynamical description. A review on the application of hydrodynamics to heavy-ion collisions has been presented in [2].

In this contribution we will concentrate on an overview and on some recent results on the microscopic rates and their computation, focusing on the thermal phase. We will treat real photons and virtual photons (dileptons). An overview of the phenomenological aspects has been presented in [3].

From a theorist's perspective, the determination of the photon and dilepton rates boils down to evaluating the same function with different kinematical conditions and prefactors. In more detail, at leading order in QED (in α) and to all orders in QCD the photon production rate per unit phase space is (see for instance Ref. [4])

$$\frac{dN_\gamma}{d^4X d^3\mathbf{k}} \equiv \frac{d\Gamma_\gamma}{d^3\mathbf{k}} = -\frac{1}{(2\pi)^3 2|\mathbf{k}|} W^<\big(k^0 = k\big), \tag{1}$$

whereas the dilepton rate reads

$$\frac{d\Gamma_{l\bar{l}}}{d^4K} = -\frac{2\alpha}{3(2\pi)^4 K^2} W^<(K)\theta\big(\big(k^0\big)^2 - \mathbf{k}^2\big). \tag{2}$$

where $K^2 = (k^0)^2 - k^2$ is the virtuality of the dilepton pair, assumed much greater than $4m_l^2$. Both rates are given in terms of the photon polarization $W^<(K)$, which reads

$$W^<(K) \equiv \int d^4X e^{iK\cdot X}\, \mathrm{Tr}\, \rho J^\mu(0) J_\mu(X). \tag{3}$$

The main elements for the determination of this expression are the *electromagnetic current* J, which describes the coupling of photons to the medium degrees of freedom and the *density operator* ρ, determining the state of these d.o.f.s. In most cases the equilibrium approximation is taken, so that $\rho \propto \exp(-\beta H)$ and Eq. (3) becomes a thermal average. When convoluting over the macroscopic evolution this corresponds to assuming a local equilibrium in each discrete medium element.[1] Later on we will mention some calculations that go beyond the local equilibrium approximation. Finally, an action or Lagrangian is necessary for the evaluation of Eq. (3), describing the propagation and interaction of the medium d.o.f.s.

Approaches for the evaluation of Eq. (3) in the thermal phase include perturbation theory, the lattice and holographic techniques. In the first, the standard QCD action is employed and the current is simply the Dirac current. The thermal average can also be generalized to out-of-equilibrium situations. This method is justified when $g \ll 1$; when applied to a more realistic coupling of $\alpha_s \sim 0.3$ it becomes an extrapolation, whose systematics may not be in full control. In Sections 2 and 3 we will describe the basics of perturbative calculations and show how recent next-to-leading order determinations can be used to test the reliability of the leading-order computations, which are widely employed in phenomenological descriptions.

On the lattice, one employs the Euclidean QCD action and computes the path integral numerically in the equilibrium case. Eq. (3) is however defined in Minkowskian space. Hence, a highly

[1] Eq. (3) is strictly speaking not correct in a full out-of-equilibrium case, as translation invariance has been used to factor out one spacetime integration. The generalization is however straightforward.