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Nuclear and Particle Physics Proceedings 276–278 (2016) 305–308
www.elsevier.com/locate/nppp

The thermal dilepton rate at NLO at small and large invariant mass

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Abstract

We report on a recent next-to-leading order perturbative determination of the dilepton rate from a hot QCD plasma for frequency and momentum of the order of the temperature and for much smaller invariant mass $M \sim gT$. We briefly review the calculation, which generalizes the previous one for the photon case ($M = 0$). We then analyze the consequences of the new calculation for the extraction of the photon rate from the small mass dilepton measurements. We then review a recent NLO determination at large M and we show how to match and merge its results with the low-mass ones, resulting in a single rate which is NLO-accurate over the phenomenologically relevant region.

Keywords: Dileptons, Hard Probes, Quark-Gluon Plasma, High order calculations, Lattice QCD

1. Introduction

Electromagnetic (EM) probes have long been considered a key *hard probe* of the medium produced in ultrarelativistic heavy-ion collisions. Their chief advantage is that they are weakly coupled to the plasma, so that their reinteractions with it can be considered negligible. EM probes hence carry direct information about their formation process to the detectors, unmodified by hadronization or other late time physics.

In this contribution we will concentrate on dileptons. Compared to photons, the kinematics of dileptons is described by two parameters, the frequency k^0 and the momentum k, with the related invariant mass $M \equiv \sqrt{k_0^2 - k^2}$. From an experimental point of view, dileptons, compared to photons, have the advantage of a smaller background from meson decays, which needs to be subtracted. For this reason, experimentalists have also focused on small-mass dileptons, which can be thought of as massive off-shell photons. Provided the mass of the pair is above the pion mass, the pion decay background is absent and the foreground rates are under much better control. For this reason, e^+e^- pairs with M somewhat above m_π^2 have been measured, to serve as an *ersatz* photon rate measurement [1, 2, 3].

In this contribution we will then first illustrate a recent perturbative calculation of the thermal dilepton rate at small M (and for $k \sim T$) to NLO [4], extending the previous work on real photons [5], aiming also at understanding whether the rate, as a function of M, is smooth enough in going from $M = 0$ to finite M, so that the ersatz photon rate measurements are meaningful. We will afterwards show the results of an NLO calculation at larger M [6] and then show how the small- and large-M computations can be merged [7, 4], resulting in a rate that is reliably NLO for most invariant masses. Another motivation for these NLO calculation is to assess the reliability of the pQCD rates, widely employed in phenomenological analyses, when extrapolated to $\alpha_s \sim 0.3$ where the coupling g is not small. We will then conclude by remarking on the implications of the results on this matter, with an outlook to comparisons with non-perturbative lattice data. In all cases the starting point is the formula giving the dilepton production rate per unit phase space at leading order in QED (in α) and to all orders in QCD. It reads (see for instance Ref. [8])

$$\frac{d\Gamma_{l\bar{l}}}{d^4K} = -\frac{2\alpha}{3(2\pi)^4 K^2} W^<(K)\,\theta((k^0)^2 - \mathbf{k}^2)\,, \qquad (1)$$

where $K^2 = (k^0)^2 - k^2 = M^2$ is the virtuality of the dilep-

http://dx.doi.org/10.1016/j.nuclphysbps.2016.05.070

ton pair, assumed much greater than $4m_l^2$. The rate is given in terms of the photon polarization $W^<(K)$, which reads

$$W^<(K) \equiv \int d^4X e^{iK\cdot X} \mathrm{Tr}\rho J^\mu(0) J_\mu(X) \,. \qquad (2)$$

Here $J^\mu = \sum_{q=uds} e_q \bar{q}\gamma^\mu q$ is the EM current and we work in thermal equilibrium, so that the $\rho = e^{-\beta H}$ and the Hilbert space trace becomes a thermal average.[1] We will work perturbatively in the strong coupling g, meaning that we treat the scale gT (the *soft scale*) as parametrically smaller than the scale T (the *hard scale*).

2. NLO at small M

By small M we mean $M \sim gT$ (and $k \sim T$), so that, as we will show, the calculation shares many similarities with the one for real photons [5]. In a naive perturbative expansion the leading order term would be the *Born term*, corresponding to the amplitude of the simple diagram shown in Fig. 1. However, its contribution to $W^<$

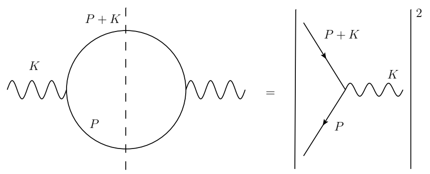

Figure 1: The Born diagram on the left and the cut corresponding to the squared amplitude for the *thermal Drell-Yan process* on the right. The plain lines with arrows are quarks and the photon is understood to be virtual; its decay in the dilepton is not shown.

scales approximately like M^2, so that in our case its contribution is suppressed and other processes, apparently of higher loop order, contribute at the same (leading) order in g. These are the $2 \leftrightarrow 2$ *processes* shown in Fig. 2 and the collinear processes shown in Fig. 3. The former

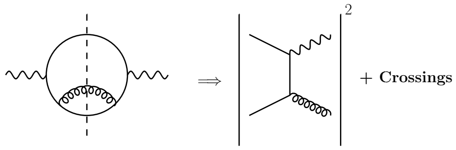

Figure 2: $2 \leftrightarrow 2$ processes. $1 \leftrightarrow 3$ processes can be shown to be suppressed for $M \sim gT$.

require some care when the t or u channel exchanged

[1]A calculation in an off-equilibrium setting relevant for heavy-ion collisions has been presented at this conference in [9].

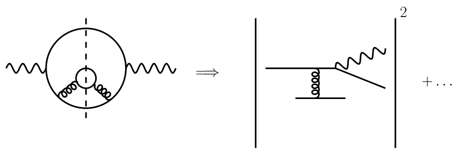

Figure 3: Collinear processes.

quark become soft: the resulting logarthmic divergence is cured by Hard Thermal Loop resummation [10, 11]. At these small virtualities the calculation is unmodified w.r.t. the real photon one.

Collinear processes are apparently suppressed w.r.t. the $2 \leftrightarrow 2$ ones. However, they receive an enhancement when the quark and antiquark (in the annihilation case) or the outgoing quark and the photon (in the bremsstrahlung case) are collinear. Furthermore, the soft scatterings that induce the splitting/annihilation are so frequent that, within the photon's formation time, many of them can occur and interfere, in what is called the Landau-Pomeranchuk-Migdal (LPM) effect. Its treatment require the resummation of an infinite number of ladder exchanges of spacelike HTL gluons. This has been done for photons first [12] and later extended to small-M dileptons [13]. In the latter case it is important to note that the Born term in Fig. 1 is the zeroth-order term in the ladder resummation series, and is thus included in the treatment of the LPM effect.

In summary, the leading-order result can be written as[2]

$$W^<(K)_{\mathrm{LO}} = \frac{8\alpha_{\mathrm{EM}} n_F(k) g^2 T^2}{3} \Bigg[\ln\left(\frac{T}{m_\infty}\right) + C_{2\leftrightarrow 2}\left(\frac{k}{T}\right) + C_{\mathrm{coll}}\left(\frac{k}{T}, \frac{M}{gT}\right) \Bigg], \qquad (3)$$

where the logarithm comes from the screening of the aforementioned divergence and $m_\infty^2 = g^2T^2/3$ is the thermal mass of quarks. $C_{2\leftrightarrow 2}$ is the coupling-independent part of the $2 \leftrightarrow 2$ processes.

At NLO both processes receive $O(g)$ corrections: the soft end of the $2 \leftrightarrow 2$ region is sensitive to the addition of one extra soft gluon and similarly the collinear sector requires the resummation of soft one-loop corrections to the ladder resummation. Furthermore a new process, the *semi-collinear* one, contributes. It can be seen as the next order in a collinear expansion, where the angle is allowed to be a bit larger. It thus interpolates between the $2 \leftrightarrow 2$ and collinear limits. The

[2]for QCD with uds light quarks