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DILEPTON PRODUCTION FROM RELATIVISTIC HEAVY ION COLLISIONS*

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Dilepton production has been proposed as one of the most promising observables to study QCD matter at extreme conditions. We review some of the main theoretical and experimental results of dilepton production in ultrarelativistic heavy ion collisions. We concentrate on dilepton emission from partonic as well as from the hadronic sources. We briefly comment about the status of theoretical calculations compared with available experimental data.

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1. Introduction

The understanding of nuclear matter at high temperatures and/or high densities is one of the major challenges in contemporary physics. For instance, QCD has predicted that under extreme conditions, nuclear matter presents different phases [1]. Lattice QCD has also provided some evidence of this prediction at low nuclear densities and high temperatures. From this calculations, there has been observed a transition from a deconfined state to a confined one around $T_{\rm c} \sim 180$ MeV [2]. This deconfined state of matter is known as Quark-Gluon Plasma (QGP), where quark and gluons are the effective degrees of freedom of the system.

The experimental realization of a hot and dense interacting nuclear matter is achieved in nucleus–nucleus collisions at ultrarelativistic energies. These collisions are able to produce high temperatures and densities within a small volume. The main objective of this experimental program is to quantify the properties of nuclear matter at extreme conditions. During the last years, different experiments performed at the Super Proton Synchrotron

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(SPS), the Relativistic Heavy Ion Collider (RHIC) and the ongoing experiments at the Large Hadron Collider (LHC) have indicated the existence of a strongly coupled plasma with partonic origin. Despite this great success, it is still difficult to have an unequivocal identification of this novel state of matter. What can be done is to have a broad set of data from different observables which, taken together, would lead us to identify the presence of a deconfined phase. Electromagnetic probes, such as high-energy photons and dileptons, are sensitive observables to the dynamics of the deconfined phase.

In this paper, we will briefly review some of the main aspects of what is known about dilepton emission in ultrarelativistic heavy ion collisions. For a more extended and completed discussion about this topic, we refer the reader to Refs. [3, 4, 5].

2. Dilepton in heavy ion collisions

Dileptons have been proposed as one of the most clear signals of the deconfined QGP [6]. These particles interact only electromagnetically, so their mean free path is larger than the typical size of the fireball. As a result, dileptons leave the strongly interacting medium created after the collision and carry information about the dynamics of the deconfined phase. Another advantage of analyzing dileptons is that their spectra are characterized by three kinematic variables, their invariant transverse mass M, their transverse momenta p_{T} and rapidity y.

In Fig. 1 we show a schematic view of dilepton production as a function of the invariant mass of the dilepton pair. From this figure, we can distinguish three kinematic regions that characterize the spectra:

1. Low mass regime (LMR): located below and around the ϕ meson, *i.e.*, $M \lesssim M_\phi = 1.024$ GeV. This region is dominated by π^0 and η decays and there are two peaks due to the vector meson decay of ρ, ω and ϕ. Medium modification of light hadrons appear in the values of their decay widths and masses.

2. Intermediate mass regime (IMR): located between $M_\phi < M < M_{J/\Psi} = 3.1$ GeV. Dilepton mass spectra is dominated by thermal emission from partonic origin. Dileptons arise from the annihilation process between quarks, $q+\bar{q} \rightarrow \gamma^* \rightarrow l^+ + l^-$ and jet conversion. The signal is obscured due to large background sources.

3. High mass regime (HMR): situated above $M \geqslant M_{J/\Psi}$. Drell–Yan production plays an important role in this regime. Medium effects may be inferred from the suppression of heavy quarkonia like J/Ψ and Υ.

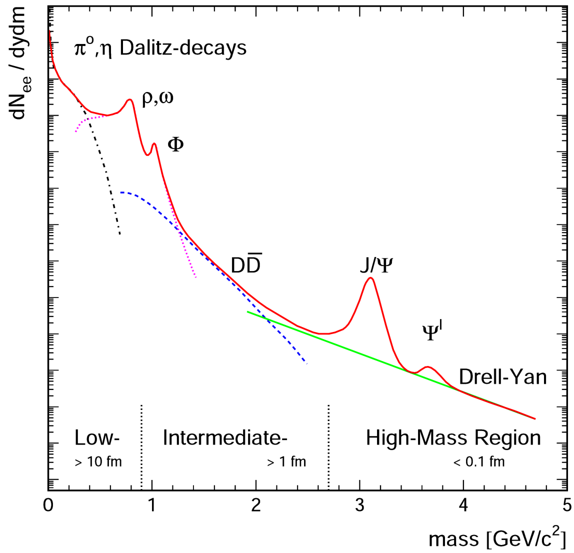

Fig. 1. A schematic view of dilepton spectra in ultrarelativistic heavy ion collisions. Figure taken from Ref. [5].

2.1. Dilepton emission rate

To make predictions and compare with experiments one needs to calculate dilepton spectra. Large mass dileptons can be calculated by using perturbative QCD. The remaining part of the dileptons comes from secondary rescatterings between the produced particles. It is often considered that dileptons are produced in a thermalized reservoir. Thus, emission of dileptons from the medium is calculated by using techniques of equilibrium thermal field theory.

The dilepton emission rate is number of dileptons per space-time per momentum volume at certain temperature T. It can be expressed in terms of the current–current correlator $\langle j_\mu(0) j_\nu(x)\rangle$, where the electromagnetic current is $j_\mu(x) = \overline{\psi}(x)\gamma_\mu\psi(x)$. To leading order in the electromagnetic coupling constant $\mathcal{O}(\alpha_e)$, dilepton production rate is given by ($Q = (\omega, \boldsymbol{q})$, $Q^2 \equiv \omega^2 - \boldsymbol{q}^2 > 0$) [7, 8, 9]

$$\frac{dN_{l^+l^-}}{d^4x d^4Q} = \frac{\alpha_e^2}{3(\pi)^2 Q^2} \frac{B g_{\mu\nu}}{e^{\omega/T} - 1} \,\mathrm{Im}\, \Pi^{\mu\nu}_{\mathrm{ret}}(\omega, q)\,, \tag{1}$$

where $\Pi^{<}_{\mu\nu}(\omega, q)$ is the electromagnetic polarization tensor

$$\Pi^{<}_{\mu\nu}(\omega, q) = \int d^4x\, e^{iQ\cdot x} \langle j_\mu(0) j_\nu(x)\rangle\,, \tag{2}$$

and the factor B indicates a threshold at $Q^2 = 4m_l^2$,

$$B \equiv \left(1 + \frac{2m_l^2}{Q^2}\right)\left(1 - \frac{4m_l^2}{Q^2}\right)^{1/2} \tag{3}$$

with m_l the mass of the lepton. Eq. (1) is valid to all orders in α_s. Dilepton emission rate can also be calculated by using relativistic kinetic theory. Both calculations are the same at leading order in $\mathcal{O}(\alpha_s)$.

To get the dilepton yields, Eq. (1) must be folded over the hydrodynamical evolution of the fireball. This introduces additional uncertainties since every evolution model has different assumptions which lead to different results when compared with real data. Different phenomenological studies indicate that the uncertainties from the hydrodynamical model are larger than the uncertainties from the thermal emission rates [10, 11].

3. Dilepton emission from hadrons

Radiation from 2 or 3 body hadron decays are the dominant in the LMR and also play an important role in the IMR. Thermal dilepton production is mainly mediated by the meson $\rho(770)$. This is a consequence of its short life time as well as its strong coupling with the pion pair. In-medium effects on the ρ mass and its decay width near the critical temperature open a window to study experimentally and theoretically the chiral symmetry restoration [12].

The dilepton rate is related to the vector spectral density of the ρ meson. Medium effects are then included in this object by using many body techniques based on effective interaction Lagrangians [9]. The parameters used in the calculations (*e.g.*, form factors) are determined by the radiative decays measurements.

4. Dilepton emission from partons

Thermal dilepton emission from partonic sources are important at high temperatures and large enough invariant masses. Two mechanisms of parton radiation contribute to dileptons: the process $q\bar{q} \to l^+l^-$ and jet conversion (annihilation between a highly energetic quark with a wavy parton of the medium) [13]. Both processes must take into account the LPM effect. This is done by using Hard Thermal Loop (HTL) technique to complete leading order $\mathcal{O}(\alpha_s)$ [14, 15]. All the phenomenological studies have assumed a thermal QGP at early times, however, non-equilibrium effects can affect the dilepton production [16]. It is also important to consider non-thermal sources of dileptons. Depending on the kinematical cuts, these can be on the same order or even higher than thermal emission. At high energies, the most important background sources are Drell–Yan annihilation process and heavy flavour decays (*e.g.*, $D\bar{D} \to e^+e^- + \mu\bar{\mu} + X$).

5. Dilepton yields: predictions vs. experimental results

The pioneering experiments which started dilepton measurements were performed by CERES/NA45 at CERN SPS [17, 18]. From the collected data, it was found an excess of radiation below the ϕ mass. Similar results were observed by Helios/3 [19] and NA38/NA50 collaborations [20]. It was concluded that $\pi\pi$ annihilation can reproduce data as far as in-medium properties of the ρ meson are included. Nevertheless, from the collected data, it was not possible to disentangle between models suggesting drop of the mass ρ and those suggesting an increase in its width [17, 18]. In 2006, the high statistics data by the NA60 Collaboration for In + In collisions at SPS energies were able to measure in medium properties of the ρ [21]. From this result, they established experimentally the models advocating the broadening of the decay of the ρ meson due to many body effects (see left panel of Fig. 2) [21, 22, 23, 24, 25].

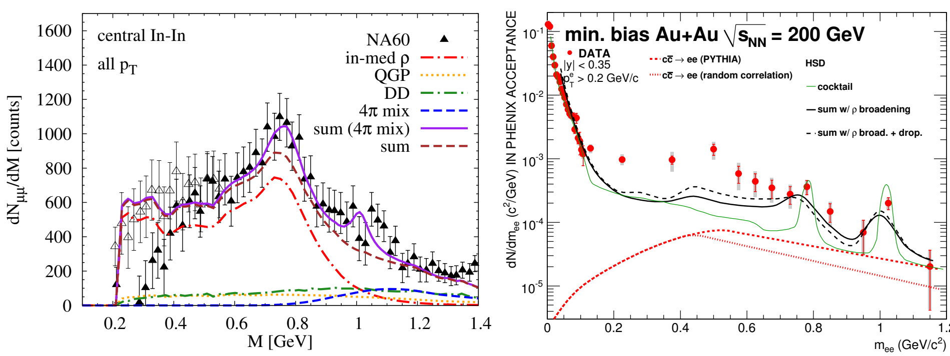

Fig. 2. Left: NA60 dimuon excess [21] in central In + In collisions at SPS compared with theoretical predictions [22]. Right: Dilepton excess measured by PHENIX Collaboration.

Recently, PHENIX Collaboration from RHIC for Au + Au collisions at $\sqrt{s} = 200$ GeV has shown an evidence of dilepton radiation excess in the LMR below ϕ (see right panel of Fig. 2) [26]. Different phenomenological studies have not been able to describe the measured data from PHENIX Collaboration [25, 26, 27]. QGP signal does not seem to be the mechanism which leads to the observed enhancement [23, 25]. It may be possible that the dilepton excess is due to some long-lived hadronic source. Still this is an open question and we hope that future planned experiments at RHIC and LHC will clarify a bit this puzzle.

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