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Electromagnetic probes of heavy ion collisions: recent developments

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Abstract

The current status of photon and dilepton emission in ultra-relativistic heavy ion collisions is reviewed, and recent developments are highlighted. The importance of emissions at early, intermediate and late times is emphasized.

Keywords: electromagnetic probes, heavy ion collisions

1. Introduction

There is compelling evidence that a plasma of deconfined nuclear matter is created in ultra-relativistic heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Analyses of soft hadron measurements suggest that this plasma approaches local thermal equilibrium rapidly ($\tau \sim 0.1$–1 fm) and proceeds to a relatively long ($\tau \sim 10$ fm) phase of hydrodynamical expansion [1]. Most soft hadrons are understood to be produced toward the end of this expansion, giving them a limited sensitivity to the properties of the earlier, hotter parts of the plasma.

Electromagnetic probes, on the other hand, have a long mean-free-path compared to the size of the plasma. They can thus escape and reach the detectors with minimum interactions with the medium, giving them the potential to provide information about the earlier stages of the deconfined plasma [2]. As such, they complement hadronic observables and provide additional constraints on the spacetime evolution of the plasma and its properties.

In ultra-relativistic proton-proton collisions, which are used as reference for heavy ion collisions, electromagnetic emission is generally well understood. Photons are produced as the result of hard parton interactions ("prompt photons") and through decays of unstable hadrons. This latter source can usually be constrained experimentally and removed from measurements, producing the observable known as "direct photons". This subtraction is difficult and often not done for dileptons, and hadronic decays constitute a large contribution to dilepton observables. Other sources of dileptons include hard parton interactions ("Drell-Yan dileptons") and decays of heavy quarks.

All sources of electromagnetic probes found in proton-proton collisions are also encountered in ultra-relativistic heavy ion collisions, all modified in one way or the other by the formation of the deconfined plasma and by cold nuclear matter effects. Additional sources of emission are induced by the deconfined plasma, such as the thermal photons and dileptons radiated by the plasma during its hydrodynamical expansion [2]. The imprint left by the plasma on thermal emissions, prompt photons, decays of heavy quarks and hadrons, and other possible sources of radiation, all constitute additional levers to help constrain the properties of the plasma.

In this contribution, the current status of electromagnetic probes in heavy ion collisions is reviewed. A discussion of early and late stage emissions is provided to put in context recent work on the subject [3]. Photons are used as example, but most considerations apply to dileptons as well. The discussion is primarily oriented toward ultra-relativistic heavy ion collisions at the LHC and at the top RHIC energy, where the description of the spacetime evolution of the plasma in terms of hydrodynamics is best understood.

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2. Electromagnetic probes: a status update

Soft electromagnetic measurements at the RHIC (Au-Au, $\sqrt{s_{NN}} = 200$ GeV) consist of the low p_T^γ direct photon spectra and anisotropies (mainly v_2 and v_3), the dilepton invariant mass spectra, and a limited measurement of the dilepton v_2 at small invariant mass [4]. The direct photon spectra was also measured at the LHC for Pb-Pb collisions with $\sqrt{s_{NN}} = 2760$ GeV, and the direct photon v_2 is under active investigations [5], with some preliminary measurements having been presented in the past.

It is generally believed that direct photon observables are dominated by thermal photons at low p_T^γ . The exponential dependence of the soft direct photon spectra is often cited as support for this conclusion, although photons produced through other mechanisms, such as interactions of hard partons with the plasma [6], could realistically produce a similar signature. Stronger support for thermal photons as the main source of low p_T^γ photons is the similarity of the direct photon v_2 and the charged hadron one in terms of size and shape: few mechanisms have been shown to be able to produce *both* a significant contribution to the low p_T^γ photon spectra with a large v_n closely resembling the charged hadron's.

As for the dilepton invariant mass spectra, in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, there are two windows around 0.3−0.6 GeV and 0.8−1.0 GeV where it is generally agreed that thermal dileptons shine above hadronic and heavy quark decays (see e.g. Ref. [7, 8]). At higher invariant mass, there are also wide regions where heavy quark decays are dominant, and can be used to study the plasma through heavy quark energy loss.

The expected importance of thermal emission is the reason behind the efforts being made to compute them with increasing accuracy. While these efforts have produced good agreement with dilepton measurements at the RHIC (e.g. Ref. [8]), comparisons of thermal photon calculations with data are still not fully satisfactory. Recent calculations of thermal photons based on a hydrodynamical description of the plasma [9] underestimate the central values of the measured spectra by up to a factor of three at the RHIC, with less tension observed at the LHC. Keeping in mind the significant experimental uncertainties, this translate into a deviation of approximately one sigma or less at the LHC, and two sigma's or less at RHIC. It must be emphasized that this tension is quantitative but not qualitative: the overall shape of the measured spectra is described well by current thermal photon calculations. As for direct photon v_n measurements, there is tension with calculations at the RHIC, especially at larger p_T^γ, but also good agreement at lower p_T^γ. Moreover, the tension at higher p_T^γ is understood to originate from the suppression of the thermal photon v_2 due to prompt photons (see e.g. Ref. [9] for more details). Calculations of the *thermal* photon v_2 are actually very similar to direct photon v_2 measurements. Consequently, as far as thermal photons are concerned, the current tension with both spectra and v_n measurements originate mainly from one cause: too few thermal photons are predicted by calculations.

In view of the above, it is still reasonable at the moment to work under the assumption that low p_T^γ direct photons are dominated by thermal photons, despite the current tension with up-to-date calculations. Various proposals that have been made to address this situation are reviewed in the next sections.

3. Thermal emission & spacetime evolution

Evaluating electromagnetic emission in heavy ion collisions requires a detailed spacetime description of the plasma, a description typically provided by hydrodynamics, although other approaches have been used [10]. Hydrodynamical models can be summarized by an initial condition, the equations of motion of relativistic viscous hydrodynamics, an equation of state, transport coefficients such as shear and bulk viscosities, and a criteria to decide when to stop describing the plasma as its temperature decreases. The usual assumption is that hydrodynamics provides a reasonable description of the plasma's expansion until its temperature drops below confinement, at which point hadronic degrees of freedom can be used. Hadronic transport models can then further describe the interactions of the resulting hadrons, and hadronic observables are evaluated once all interactions cease.

Initial conditions for hydrodynamics, usually provided at a fixed time $\tau = \sqrt{t^2 - z^2}$, are either constrained by simplified first-principle descriptions of the early-time dynamics of heavy-ion collisions, or an ansatz like the Glauber model, in both case with some parameters to be adjusted to measurements. The ansatz approach can be sufficient to study many hadronic observables, which often have a limited sensitivity to smaller features of the initial conditions. This is not necessarily sufficient for electromagnetic probes, which are emitted at all times. In this sense, a smooth transition from early time degrees of freedom to hydrodynamics is a desirable feature of hydrodynamics models of heavy ion collisions.

This continuous transition between the early plasma, the intermediate hydrodynamical expansion and the