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Thermal Radiation Mapping the Space-Time Evolution

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Abstract

Over the past decade heavy ion experiments at RHIC and now also at LHC uncovered many properties of quark matter produced in collisions of nuclei. Generally, the data is consistent with the formation of a strongly coupled plasma, which is in or close to equilibrium within a fraction of a fm/c; evolves like low viscosity/entropy liquid as described by hydrodynamic models; and is largely opaque to colored probes. Many models have been developed to describe different aspects of the observations. However, the detailed data that is now available present many challenges to theoretical models, which hints towards how incomplete our understanding currently is. In particular, PHENIX data on electromagnetic radiation is seemingly inconsistent with the standard hydrodynamic space-time evolution of strongly interacting matter and requires new sources of radiation early in the collision.

1. Goals and Context

Electromagnetic radiation, which in a wider sense includes real and virtual photons, has long been thought excellent to probe the quark gluon plasma produced in heavy ion collisions [1]. Electromagnetic radiation does not participate in the strong interaction and thus leaves the reaction volume undisturbed after its emission. Its energy spectrum reflects the energy density and collective velocity of the strongly interacting matter from which it is emitted. Thus, if the strongly interacting matter is in local thermal equilibrium, electromagnetic radiation will provide information about the space-time evolution of temperature and collective motion driven by pressure - in this sense electromagnetic radiation can be considered ”thermal” radiation, though strictly speaking it’s not in equilibrium. Even if the strongly interacting matter is not in local equilibrium, the electromagnetic radiation emitted will carry the information about the energy density and we will refer to it loosely as ”thermal”.

For real and virtual photons the temperature and collective motion information is encapsulated in the momentum spectrum and by itself it is difficult to unravel the two contributions. However, the mass of the virtual photons is Lorentz invariant and thus the mass distribution must be frame independent. Therefore, the mass distribution of the virtual photons will only be sensitive to the temperature [2]. Measuring the thermal virtual photon yield as function of mass and momentum holds the promise to separate the temperature from the collective motion and thus to map out the space-time evolution of the matter produced in the collision in a nearly theory independent way. Key to the measurement of thermal radiation is to isolate it from all the lepton pairs from hadron decays long after the collision. In order to achieve this, lepton pairs from decays of pseudoscalar, vector, and heavy flavor carrying mesons need to be measured accurately within the same experiment.

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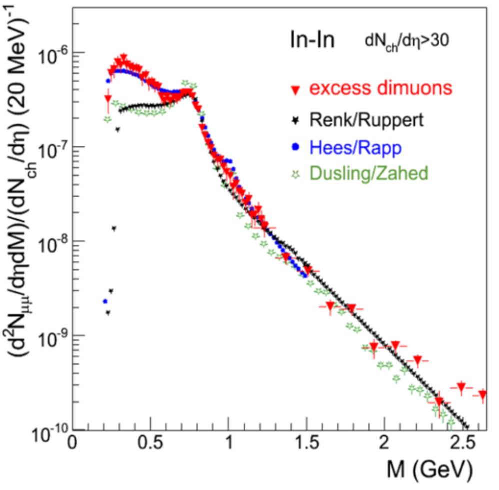

Figure 1: Invariant mass spectrum of the dimuon excess observed in In+In collisions at 158A GeV by the NA60 experiment [4, 5]. The data are integrated over m_T and fully corrected for detector acceptance. Also shown are three model calculations for thermal radiation [7, 6, 8]

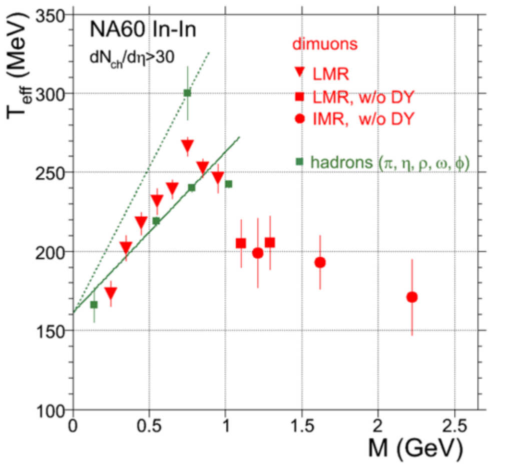

Figure 2: Inverse slope parameter of the m_T spectra corresponding to Fig. 1 as a function of mass. Inverse slopes were determined in the range).1 $< (m_T - M) <$ 1.4GeV. The inverse slope for various hadrons is shown for comparison.

2. The state of the art experiment: NA60

The SPS dimuon-experiment NA60 [3] sets the state of the art standard for dilepton measurements. They have pioneered the technique to isolate the thermal radiation and to map out its mass and momentum spectra. Fig. 1 shows the fully acceptance corrected mass spectrum with all known sources, except for the ρ meson, subtracted [4, 5]. It is compared to a set for theoretical calculations performed by different groups [7, 6, 8]. They have in common that the yield is dominated by $\pi\pi$ annihilation. For reference [7], which describes the low mass data best, a broadened spectral function related to chiral symmetry restoration is included. For masses above 1 GeV the data exhibits a nearly exponential Planck-like spectrum with an inverse slope slightly above 200 MeV. For the two model calculations that extend all the way to 2.5 GeV [6, 8] parton degrees of freedom dominate the emission of thermal radiation in this mass range; the average temperature is 217 MeV. By comparison to theoretical models one can deduce that the excess indeed is thermal dilepton radiation.

Fig. 2 explores the momentum direction of the same data. Shown are inverse slopes resulting from fits to nearly exponential transverse mass (m_T) distribution in given mass ranges [4, 5]. Below 1 GeV the dilepton data display an approximately linear increase of the inverse slope parameter with mass, which is indicative of strong collective radial expansion of the matter emitting dileptons. Extrapolating the inverse slope back to $m = 0$ gives a temperature of about 120-140 MeV, below the conjecture critical temperature. Above 1 GeV the inverse slope remains constant at about 200 MeV, consistent with the inverse slope of the mass spectrum. Since the mass distribution is insensitive to flow, this must mean that the matter radiating dimuons in this mass range does not flow. These findings are consistent with the interpretation of the mass spectrum and strongly suggest that the excess dimuons observed by NA60 are indeed thermal radiation from the matter created.

In summary, NA60 data gives detailed insight into the space-time evolution of matter produced at low energies and is certainly consistent with a standard hydrodynamic space time evolution. The emission is dominated by the $\pi\pi$-annihilation from the hot hadronic phase, which expands rapidly under pressure. However, radiation from the partonic phase is also observed, with an average temperature of about 200 MeV, above the transition temperature. Partonic matter does not seem to flow, consistent with the conjecture that at SPS energies the quark-gluon-plasma is created near the softest point in the equation of state.