Abstract

We reanalyze the WA98 single photon data at CERN SPS by incorporating several recent developments in the study of prompt and thermal photon production from relativistic heavy ion collisions. Isospin and shadowing corrected NLO pQCD, along with an optimized scale for factorization, fragmentation and renormalization are considered for prompt photon production. Photons from thermal medium are estimated by considering a boost invariant azimuthally anisotropic hydrodynamic expansion of the plasma along with a well tested equation of state and initial conditions. A quantitative explanation of the data is obtained by combining $\kappa \times$ prompt with thermal photons, where $\kappa$ is an overall scaling factor. We show that, elliptic flow of thermal photons can play a crucial role to distinguish between the ‘with’ and ‘without’ phase transition scenarios at SPS energy.

1. Introduction

The first observation of single photons by the WA98 Collaboration at CERN SPS is considered as a well anticipated turning point in the study of relativistic heavy ion collisions using electromagnetic probes. Earlier observations like the one by the WA80 Collaboration, provided only a useful upper limit of this study (for recent developments in the field of direct photon production from relativistic heavy ion collisions, see Ref. [4, 5]). The study of electromagnetic radiations, and in particular photons, as a probe of heavy ion collisions is advantageous compared to the study of hadrons, for two main reasons. First of all, photons are emitted from each and every stage of the expanding system, whereas hadrons are emitted only from the surface of freeze-out after suffering strong interactions. Secondly, photons do not suffer final state interaction (for being electromagnetic in nature, their mean free path is larger than the system size) and carry undistorted information from the production point to the detector. The major problem in the study of single photons from heavy ion collisions arises from the very small signal to background ratio. However, recent developments in the background subtraction methods have reduced the size of error bars in the direct to decay ratio for photons considerably. We reanalyze the single photon WA98 data by incorporating several new improvements in our understanding of prompt photon production from heavy ion collisions and considering the latest developments in the field of thermal photon production along with a well defined equation of state and suitable initial conditions [2].

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2. Reanalysis of single photon data at CERN SPS

2.1. Prompt photons

The study of prompt photon production in p + p collisions has reached a higher level of sophistication and all the available data have now been successfully analyzed with NLO pQCD treatment [9] without the inclusion of intrinsic k_T for protons. In particular, the suppression of single photons at large p_T for Au+Au collisions with respect to the single photons resulting from p + p collisions at the same nucleon-nucleon center of mass energy may be largely due to the difference in valence quark structure of protons and neutrons [10].

We calculate the prompt photon production from p + p collisions using NLO pQCD treatment along with an optimized scale for factorization, fragmentation and renormalization (all equal to p_T/2) at \( \sqrt{s} = 19.4 \text{ GeV} \) (without introducing intrinsic k_T) and compare our results with various experimental data available at that energy (with proper mass number normalization for p + 12C collisions). This comparison is done as no experimental data are available for p + p or n + n collisions at the WA98 center of mass energy (\( \sqrt{s_{NN}} = 17.3 \text{ GeV} \)) and the available data at the closest center of mass energy is at \( \sqrt{s} = 19.4 \text{ GeV} \) [see left panel of Fig. 1]. We see that the photons originating from fragmentation are about 30% of those produced from Compton+annihilation processes. Our result using NLO pQCD matches well with the NA3 [8] data, while it underestimates the E704 [6] and E629 [7] data, same as reported by earlier studies.

For prompt photon production from 158A GeV Pb+Pb collisions, isospin and shadowing [11] corrected NLO pQCD treatment is used with the same scaling factor of p_T/2 for factorization, fragmentation and renormalization. The effect of isospin and shadowing on photon production from heavy ion collisions are investigated by calculating nuclear modification factor (R_AA) as function of p_T and x_T (\( = 2p_T/\sqrt{s} \)) for different beam energies. Results for p+p normalized R_AA as a function of p_T for p+n, n+n, and Pb+Pb collisions are shown in right panel of Fig. 1. We see that the photon production from Pb+Pb collisions is suppressed significantly in the intermediate and high p_T range, compared to the production from p+p collisions.

2.2. Thermal photons

For thermal photons, centrality dependent azimuthally anisotropic boost invariant ideal hydrodynamics is used along with different sets of initial parameters. A well tested equation of state
is used considering a first order phase transition from the plasma state to the hadronic phase at a transition temperature \( T_c \) (\( \sim 164 \) MeV). The initial energy density profile is taken as proportional to the number of wounded nucleons and five different values of \( \tau_0 \) are considered ranging from 0.2 fm/c to 1.0 fm/c (in steps of 0.2 fm/c) keeping the total entropy of the system fixed. The time evolution of average energy density \( \langle e \rangle \), average temperature \( \langle T \rangle \) and average radial flow velocity \( \langle v_T / c \rangle \) at different \( \tau_0 \) are compared. We find that the values of \( \langle e \rangle \) (\( \sim T^4 \)) changes significantly at large \( \tau \) with changing values of \( \tau_0 \), whereas \( \langle T \rangle \) and \( \langle v_T / c \rangle \) are not affected much [see Ref. [2] for detail]. Also, the effective temperature, \( T_{eff} = T \sqrt{(1 + v_T / (1 - v_T))} \), (or the blue shifted temperature) is calculated as function of proper time at different \( \tau_0 \) to see the combined effect of cooling and expansion (velocity). Thermal photons at different \( \tau_0 \) are calculated considering standard rates (QGP photons from Ref. [12], and HM photons from Ref. [13]) of photon production for 0-10% most central collisions with freeze-out energy density of about 0.075 GeV/fm^3.

We find that the prompt photon production is about 17% of the total yield measured by WA98 and the thermal photon result is almost similar to prompt photon production at \( \tau_0 = 0.4 \) fm/c. We also note that the thermal photons from hadronic phase are not affected significantly with changing \( \tau_0 \). A quantitative description of the WA98 experimental data is obtained by using the relation ‘Thermal + \( \kappa \times \) Prompt’ where, \( \kappa \) is adjusted to reproduce the photon production at \( p_T = 2.55 \) GeV/c. For all \( \tau_0 \), a normalization at the same \( p_T = 2.55 \) GeV/c provides a good description of the data in the entire \( p_T \) range. We find that the scaling factors \( \kappa = 2.7, 4.9, 5.4, 5.7, \) and 5.9 for prompt photons at \( \tau_0 = 0.2, 0.4, 0.6, 0.8, \) and 1.0 fm/c respectively provide a good quantitative agreement with the WA98 data [shown in Fig. 2]. We argue that the factor \( \kappa \) for prompt photons accounts for the Cronin effect, in the case of nucleus-nucleus collisions, as well as a pre-equilibrium contribution which must surely be included when \( \tau_0 \) is large.

2.3. Elliptic flow of photons and hadrons

In a potentially interesting observation we show that, one additional experimental result, i.e, the elliptic flow for thermal photons [14] could actually distinguish between the different values of \( \tau_0 \). The elliptic flow results for different \( \tau_0 \) along with the hadronic matter contribution for 158A GeV Pb+Pb collisions at CERN SPS are shown in right panel of Fig. 3. We note that several earlier studies have explained the WA98 data considering only the formation a hot hadronic gas in the collision and without the formation of QGP phase [15]. The estimation of photon flow at
SPS can distinguish between the two scenarios of 'with' and 'without' phase transitions as the nature of $v_2$ would be completely different in the two cases. We also compute the particle spectra and $v_2(p_T)$ for several hadrons and show explicitly that both the spectra and elliptic flow results remain unaffected with changing values of $\tau_0$ for hadrons. $v_2(p_T)$ for $\rho$ mesons at different $\tau_0$ are shown in right panel of Fig. 3.

In conclusion, we present a quantitative explanation of the WA98 single photon data at CERN SPS by incorporating several recent developments in the field of prompt and thermal photon production from heavy ion collisions. Thermal photons at different $\tau_0$ along with prompt contribution enhanced by a `$\kappa$' factor describes the data quite well in the entire $p_T$ range. We also show that thermal photon $v_2$ can distinguish between the different $\tau_0$ and phase transition scenarios at SPS energies.

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