e^+e^- pairs: a clock and a thermometer of heavy ion collisions

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Abstract. Recently, there is growing evidence that a new state of matter is formed in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at RHIC: a strongly coupled Quark Gluon Plasma of partonic degrees of freedom which develops a collective motion. Dilepton spectra are not affected by strong interaction and can therefore probe the whole time evolution of the collision. Thus they may be sensitive to onset of deconfinement, chiral symmetry restoration, as well as the production of thermal photons. The PHENIX experiment measured the production of $e^+e^-$ pairs in p+p and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. An enhanced dilepton yield in the mass range $150 < m_{ee} < 750$ MeV/c^2 is measured. The excess increases faster with centrality than the number of participating nucleons and is concentrated at $p_T < 1$GeV/c. At higher $p_T$ the excess below 300 MeV/c^2 has been related to an enhanced production of direct photons possibly of thermal origin.

1. The role of dileptons and photons in heavy ion collisions

One of the main goals in nuclear physics is to investigate QCD and its properties under extreme conditions of hot and dense matter. These conditions are experimentally realized in relativistic heavy ion collisions, which create a fireball where the energy density by far exceeds typical hadronic values and fundamental constituents of matter, quarks and gluons, are no longer confined to color neutral hadrons. Lattice QCD calculations indicate that this significant change in the structure of matter coincides with the restoration of chiral symmetry, which is linked to the origin of the hadron masses [1]. Experimental results from the Relativistic Heavy Ion Collider (RHIC) have established the formation of such Quark Gluon Plasma in Au+Au collisions at $\sqrt{s_{NN}}=200$GeV [2]. A large set of data allows to characterize the nature of the medium created. It has very high density, as indicated by the large energy loss of light and heavy quarks, and thermalizes rapidly, as indicated by the significant elliptic flow of the same partons. Many open questions remain, for example: what is the temperatures, the corresponding system sizes of the matter at the early stages, and the temperature evolution of the system from the formation time to thermal freeze-out? Is chiral symmetry restored? While signatures of chiral symmetry restoration manifest themselves in non-observable order-parameters (such as the quark condensate), links can be established with the hadronic excitations and modifications of their fundamental properties, such as mass, width and life-time.
Electromagnetic probes, such as real and virtual photons (i.e. dileptons), provide key measurements to address these open questions. Created through the entire space-time evolution of the system, they escape, once emitted, from the strongly-interacting medium without final-state interaction. The measurement of direct thermal radiation (photons or dileptons) can be used to derive a limit on the initial temperature of the QGP created in heavy ion collisions at RHIC. Moreover, dileptons production is mediated in the hadronic phase by light vector mesons, in particular to $\rho$ (770), whose sufficiently small lifetime (1.3 fm/c), and whose strong coupling to the $\pi-\pi$ channel makes it as a prominent probe for in-medium modifications of hadron properties.

2. Review the results from the pre-RHIC era

Dileptons and photons have already received attention in the SPS program. An enhanced dilepton yield in the low mass region (LMR: $m < 1$ GeV) with respect to the sum of known hadronic sources was first reported by CERES [3] and HELIOS [4] in S+Au and S+W reactions at 200 AGeV. The discovery triggered numerous theoretical interpretations [5] which concentrated on the role of $\pi-\pi$ annihilation $\pi^+\pi^- \leftrightarrow \rho \rightarrow e^+e^-$. Theoretical approaches based on in-vacuum properties of the $\rho$ systematically failed to describe the data. More successful was theoretical work with medium-modified spectral functions, including scenarios where the mass of the $\rho$ meson drops, according to the Brown-Rho scaling conjecture, or broadens by strongly interacting with the hot and dense medium. The CERES data also show that such enhancement rises significantly steeper than linearly with charged particle density and is concentrated at very low pair-$p_T$, consistent with the interpretation that the excess is due to binary annihilation processes [6]. NA60 recently confirmed the excess of pairs in In+In collisions at 158 AGeV [7] and analyzed the slope parameter $T_{eff}$ from the corresponding pair-$p_T$ spectra which rises with dilepton mass consistent with the expectations of radial flow of the hadronic decay source [8, 9]. Several recent theoretical works reasonably reproduce features like the mass distribution of the enhancement, the centrality dependence, and the radial flow of the source. However, the pair-$p_T$ spectra exhibit a steep rise towards low pair-$p_T$ that has not been explained by any model so far [10].

An excess of dilepton pairs has also been observed by NA38/NA50 [11] in the intermediate mass region (IMR: $1 < m < 3$ GeV), where the sensitivity to thermal radiation increases. NA60 data suggest that this enhancement cannot be attributed to decays of D-mesons but may result from prompt production, as expected for thermal radiation. The sudden drop of the slope parameter $T_{eff}$ above 1 GeV/c$^2$ in mass, advocate a partonic (i.e. non-flowing) origin of this direct radiation [12, 8, 9]. While similar kinematic window, $q_T = \sqrt{m^2 + p_T^2} = 2$ GeV, was addressed by WA98 [13] to measure direct photon spectra, the two points at low $p_T$ extracted via HBT methods challenged the existing predictions which could reconcile with the data only after the inclusion of soft Bremsstrahlung [14] off $\pi\pi$ and $\pi K$ from the late stages of the fireball.

3. The new results at RHIC

The PHENIX experiment at RHIC extends dileptons and photon measurements with the analysis of $p+p$ and $Au+Au$ collisions in a new energy regime of $\sqrt{s_{NN}}=200$ GeV. Thanks to its versatility in particle identification, high granularity and high rate capability, PHENIX can measure electrons and photons with high precision at...
mid rapidity and muons at forward rapidity. Detailed descriptions of the electron pair analyses can be found in [15, 16, 17]. The pair-signal is compared to a cocktail of hadronic sources, semi-leptonic decays of heavy quarks and Drell-Yan.

In p+p collisions PHENIX has measured the spectra of pions [19, 20], kaons [19, 20], ω [22], φ [23], J/ψ [24] via several decay channels, see Figure 1. Pions are fitted with a modified Hagedorn function; the other data are fitted with the same function scaled with \( m_T \) and a free normalization factor. Excellent agreement with the data is achieved. Figure 2 shows the \( e^+e^- \) pair yield as a function of pair mass for p+p (left) and Au+Au (right) both compared to an absolutely normalized cocktail tuned for the respective collision system. The contribution from heavy quark decays has been fitted to the p+p data using the \( e^+e^- \) pair distribution predicted by PYTHIA [25]. The charm cross section was found to be 
\[
\sigma_{c\bar{c}} = 544 \pm 39\text{(stat)} \pm 142\text{(syst)} \pm 200\text{(model)} \mu\text{barn}
\]
consistent with QCD calculations and with more precise measurements from single leptons (567 \pm 57\pm 193 \mu\text{barn} [18]). This latter was used for the Au+Au cocktail, scaled by the average number of binary collisions (258 \pm 25) [26]. The p+p data agree very well with the sum of all known sources.

In Au+Au the data below 150 MeV/c^2 are well described by the cocktail of hadronic sources. The vector mesons ω, φ and J/ψ are reproduced within the uncertainties. However, in the mass region from 150 to 750 MeV/c^2, the yield is enhanced above the expectations by a factor of 3.4 \pm 0.2\text{(stat)} \pm 1.3\text{(syst)} \pm 0.7\text{(model)}, where the first error is the statistical error, the second the systematic uncertainty of the data, and the last error is an estimate of the uncertainty of the expected yield from the cocktail. Above the φ meson mass the data seem to be well described by the continuum calculation based on PYTHIA. However the observation of a strong suppression and a large \( v_2 \) of single electrons from heavy quark decays suggest that charm might be thermalized [27]. This may correspond to a loss of the dynamical correlation of c and \( \bar{c} \) quarks indicated by the second charm curve (Fig. 2 right), which leads to a much softer mass spectrum and would leave room for significant other contributions, e.g. thermal radiation.

3.1. The centrality dependence

To shed more light on the possible origin of the Au+Au enhancement, the centrality and the \( p_T \) dependence of the continuum yield are studied. Using simulations based on
The yield in the mass region 1.2 to 2.8 GeV/c is dominated by low number of participating nucleon pairs \((N/2)\). While the yield below 100 MeV/c\(^2\), which is dominated by low \(p_T\) pion decays, agrees with the expectation from the hadron cocktail, the yield in 150–750 MeV/c\(^2\) rises significantly compared to the expectation, qualitatively consistent with the conjecture that an in-medium enhancement of the dielectron continuum yield arises from scattering processes like \(\pi\pi\) or \(q\bar{q}\) annihilation.

The yield in the mass region 1.2 to 2.8 GeV/c\(^2\) normalized to the number of participating nucleon pairs \((N/2)\) or per binary collisions \(N_{\text{coll}}\) for three different mass ranges compared to the expected yield from the hadron decay model [15].
binary collisions (Fig. 3 right) shows no significant centrality dependence and is consistent with the expectation based on PYTHIA. However the scaling with $N_{coll}$, expected for charmed meson decays [27], may be a mere coincidence resulting from two balancing effects: the suppression of charm which increases with $N_{part}$ and a thermal contribution could increase faster than linearly with $N_{part}$. Such a coincidence may have been observed at the SPS [11], where a prompt component has now been suggested by NA60 [12].

3.2. The $p_T$ dependence

Figure 4 compares $e^+e^-$ pair invariant mass spectra measured in p+p and in Au+Au collisions to the corresponding expectations from the cocktail of hadron decays and open charm, in different ranges of $p_T$. The p+p, the Au+Au data and the cocktail are normalized relative to each other in $m < 30$ MeV/c$^2$.

The p+p data is consistent with the expectations from the cocktail over the full mass range and in every $p_T$ bins, except for some small deviations in the higher $p_T$ bin (see discussion of high $p_T$ below). In contrast, the low-mass enhancement in Au+Au is concentrated at low-$p_T$, as shown in the Figure: the $p_T$ bin $p_T < 0.7$ GeV/c is enhanced more than the inclusive data, the bin $0.7 < p_T < 1.5$ GeV/c is enhanced less than the inclusive data, and in the last one $p_T > 1.5$ GeV/c the Au+Au data almost agree with the p+p data.

Fig. 4 shows the transverse momentum spectra for different mass windows for Au+Au and p+p data and the expected contribution from hadronic cocktail and charmed mesons. In the low mass bins (up to 400 MeV/c$^2$) the yield is truncated at low pair-$p_T$ due to the single-track $p_T$ cut at 200 MeV/c. In contrast to the mass spectra, the $p_T$ spectra are corrected for the acceptance, therefore represent the invariant yield within $|\eta| \leq 0.5$ in pseudo-rapidity and $\phi = \pi/2$ in azimuth.

In the low-$p_T$ region ($p_T < 1$ GeV/c) all the p+p spectra are consistent with the expectations from the cocktail. The Au+Au data agree with the cocktail only in the region $m < 100$ MeV/c$^2$, while in all the higher mass bins the data show an excess that grows towards low-$p_T$ despite the $p_T > 200$ MeV/c cut on the single electron track. The Au+Au spectra indicate a change of slope around 1 GeV/c. To extract
information about the low-\(p_T\) component the Au+Au spectra was fitted with an exponential in \(m_T\) in two mass regions. The first fit is restricted to the low-\(p_T\) region (\(p_T < 1 \text{GeV}/c\) and the second to a region where the data seem to follow the trend of the cocktail (\(1 < p_T < 2 \text{GeV}/c\)). To account for the contribution of the cocktail below the low-\(p_T\) component, the spectra were fitted with the sum of two exponentials; alternatively a modified Hagedorn function was fitted to the mass range \(m_{ee} < 0.1 \text{GeV}/c^2\) and then \(p_T\)-squared to larger masses. The extracted values of \(T_{eff}\) are shown in Fig. 6 (left) as a function of mass, together with the slopes of identified hadrons measured by PHENIX [30]. The hadron slopes rise linearly with mass, consistent with the expectations from radial expansion of the hadronic source. The slope of the \(e^+e^-\) pair spectra in the range \(1 < p_T < 2 \text{GeV}/c\), where the data are in reasonable agreement with the cocktail, seems to follow this trend. In contrast, the slope of the low-\(p_T\) component remains approximately constant at \(\approx 120 \text{ MeV}\) and does not show the rise with mass typical for a radially expanding source. Fig. 6 (right) shows the
$e^+e^-$ yield in each mass range obtained by integrating the $p_T$ spectra. The panel also shows the yield of the low-$p_T$ exponential extracted from the two fits described above (2 exponentials or exponential + $m_T$-scaled Hagedorn function). In either case the yield of the low-$p_T$ exponential contributes at least 50% of the yield of the spectra.

While most of the $e^+e^-$ yield pair enhancement in Au+Au is concentrated at $p_T < 1$ GeV/c, some enhancement is also observed at higher $p_T$. PHENIX has also analyzed this in the $p_T$ region 1 < $p_T$ < 5 GeV/c by comparing the spectra in p+p and Au+Au collisions to the expectations from the cocktail, as shown in Fig. 7. The p+p data are consistent with the cocktail with only a small excess in the higher $p_T$ bins, while Au+Au data show a much greater excess. In the mass region $m_{ee} < 300$ MeV/c$^2$ little or no contribution is expected from conventional sources since $\pi^+\pi^- \rightarrow e^+e^-$ can only contribute for $M_{ee} \geq 2M_{\pi}$. Since any source of real photons can also emit virtual photons which convert to low mass $e^+e^-$ pairs, the excess was analyzed under the assumption that it is entirely due to internal conversion of direct photons which result in a mass distribution following the description by Kroll and Wada. A two-component fit which uses the relative fraction of direct photons as only free parameter, allows to determine the fraction of direct photon component, consistent with the expectations from NLO pQCD in p+p, but larger than the $N_{coll}$-scaled calculations in Au+Au. This is converted to the invariant cross section/yield of direct photons, shown in Fig 7. The Au+Au data are fitted with an exponential plus a modified power-law function fixed to the p+p data and scaled by $T_{AA}$; the inverse slope $T = 221 \pm 23$ (stat) $\pm 18$ (sys) is related to the initial temperature $T_{init}$ which, according to hydrodynamical models, is 1.5 to 3 times larger than $T_{init}$.

4. Conclusions

Measurements of Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV show an enhancement of the dielectron continuum in the mass range 150–750 MeV/c$^2$ in central collisions. The
enhancement is absent in p+p and peripheral Au+Au collisions, where the observed yield agrees well with the calculated hadron decays contributions. The enhancement increases with centrality faster than proportional to $N_{\text{part}}$. Moreover the enhancement is concentrated at low-$p_T$ with an inverse slope $T_{\text{eff}} \sim 120\text{MeV}$ which does not exhibit a mass dependence and thus probably does not participate in radial collective flow. This low-$p_T$ enhancement is qualitatively consistent with data from SPS experiments \cite{6, 7}. None of the currently available theoretical models yet explains this low-$p_T$ component. At $1 < p_T < 5\text{GeV/c}$ the p+p data show a small excess over the hadronic background while the Au+Au data show a much larger excess. Treating the excess as internal conversion of direct photons, a direct photon yield is deduced. It is consistent with NLO pQCD calculations in p+p. In Au+Au it is consistent with hydrodynamical models with initial temperature $T_{\text{init}} \sim 300 - 600\text{MeV}$ at times of 0.6-0.15 fm/c.

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