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Dilepton production in proton-proton collisions at top RHIC energy

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Abstract. We study dielectron production in proton-proton collisions at top RHIC beam energy within an extended statistical hadronization model. The invariant mass spectrum of correlated dielectron pairs is evaluated in the low invariant mass region and calculated results are compared with the PHENIX experiment. The model is found to be able to describe the data very well up to invariant masses of 1 GeV with few adjustable parameters.

1. Introduction

Correlated dilepton radiation has been considered for a long time to be an important tool to study the hot and dense nuclear matter created in relativistic nuclear collisions. The idea behind is that dileptons are emitted during all stages of the collision evolution and the electromagnetic cross sections with the created medium are believed to be small and so electromagnetic signals from the early stages might survive the preceding evolution of the system. Thus, by studying the dilepton emission one can extract information also on the earlier, possibly exotic phases of the collision evolution. For this to hold true, however, one has to carefully model the final (and dominant) stages of the collision evolution where dilepton radiation is predominantly governed by the decays of light mesons.

The PHENIX collaboration has recently measured the correlated dielectron invariant mass spectrum in proton-proton [1] as well as in $Au + Au$ [2] collisions at the top RHIC beam energy. A large and so far un-explained excess of dielectrons in (semi)central heavy-ion collisions is seen in the data below the mass of ϕ meson when compared with various model calculations while the spectrum in $p + p$ collisions can be fairly well understood within the hadronic freeze-out cocktail calculations [1]. We present in this paper our baseline hadronic freeze-out cocktail calculation for the dielectron production in proton-proton collisions in the low invariant mass region while the analysis of the heavy-ion collisions as well as an extension to invariant masses larger than the ϕ meson mass will be presented in a forthcoming publication [3].

2. Statistical hadronization model

The statistical hadronization model (SHM) has been used successfully in describing the hadronic yields and rapidity densities in high energy proton-proton collisions at SPS and RHIC [4-7]. In this work we employ the simplest version of the SHM, i.e. the analysis is performed in the grand-canonical ensemble, because calculations become considerably easier once we do not require exact conservation of conserved quantities. The price to pay for the easier calculations is that one has

to introduce a free parameter for each of the conserved quantities that are conserved in average only.

In the SHM, the primary hadron multiplicity of hadron type i is calculated (omitting the fugacities) according to

$$N_i = V \frac{2J_i + 1}{(2\pi)^3} \int \gamma_S^{n_s} \, e^{-\sqrt{p^2 + m_i^2}/T} \, d^3 p. \tag{1}$$

In Eq. (1) J_i denotes the spin, p the three-momentum and m_i the mass of the particle of the hadron species i. In principle the model has 6 free parameters: T, μ_B, μ_Q, μ_S, γ_S and the system volume V, but we know that the central rapidity region is close to net charge free[1] and, furthermore, the dilepton radiation is dominated by decays of neutral mesons, whose multiplicities do not depend explicitly on the chemical potentials, and thus to a good approximation we can set the chemical potentials to zero. In this case we are left with 3 free parameters (T, γ_S and V) that describe the yields of all relevant hadrons. The γ_S (< 1) [8] parameter takes into account the empirical fact that the SHM tends to over-estimate the strange hadron yields in the elementary particle collision systems.

The SHM has been fitted to the STAR data measured in the central rapidity region in $p + p$ collisions [7] and we use the resulting fit parameters $T = 170$ MeV and $\gamma_S = 0.6$ in our analysis. We have re-adjusted the system volume such that the π^0 rapidity density at mid-rapidity is reproduced. All calculations are performed assuming that in each of the events there is only one large cluster produced. This picture is justified under special assumptions discussed for example in [9]. For the resonances with width larger than 2 MeV, Eq. (1) is convoluted with the relativistic Breit-Wigner distribution in order to take into account the finite widths of the resonant states and the two dimensional integration over the momentum and mass is performed in order to calculate the primary yields.

The evaluation of the dilepton emission with the SHM proceeds as follows: First, we calculate the mean primary yields of different hadrons according to Eq. (1) and then - using these values - we sample event-by-event Poisson distributions for the primary yields of all hadrons and resonances. Thus, even though the temperature, γ_S and the system volume are kept the same for all events, we have somewhat different amounts of primary hadrons produced in each of the events and so the energy, for example, is not fixed but fluctuates from event to event.

Next, unstable resonances decay into stable ones and as a final step, we let the vector mesons decay into dielectrons. The branching ratios of different hadrons and resonances into dileptons are typically very small and thus we take into account the dilepton radiation from the dominant sources only, which at RHIC energies are the low mass vector mesons. We do not consider the direct dilepton emission from most of the resonances in the cases where the contribution would be negligible. One should notice, however, that in our approach it is important to include all the known resonances (≈ 300) because eventually they decay into the light mass vector mesons[2] and thus indirectly affect the dilepton yields. The dilepton channels taken into account in our analysis are listed in Table 1.

In general, the probability of a hadron to decay into a certain channel depends both on the mass of the parent hadron as well as on the energies of the daughter particles. We have evaluated in detail the mass dependent partial widths into dileptons as well as the total widths of the vector mesons in this analysis while for the resonance decays, which do not directly produce dielectrons, we have taken into account trivial mass threshold effects only in our analysis. Formulae for the dielectron partial widths are known from the literature and we have used the standard

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[1] estimates for the μ_B in the central rapidity region vary from around $20 - 30$ MeV in central $Au + Au$ collisions to around 10 MeV in $p + p$ collisions ; $\mu_S \approx \mu_B/4$ and $\mu_Q \approx \mu_B/40$ are thus also small

[2] for example about half of the ρ^0 mesons are produced primarily while the other half come from resonance decays

Table 1. Decay channels relevant for dielectron production in $p + p$ collisions at $\sqrt{s}$=200 GeV.

Hadron	direct	Dalitz	other
π^0		$\pi^0 \to \gamma\, e^+ e^-$	
η^0		$\eta^0 \to \gamma\, e^+ e^-$	$\eta^0 \to \pi^+ \pi^- e^+ e^-$
η'		$\eta' \to \gamma\, e^+ e^-$	$\eta' \to \pi^+ \pi^- e^+ e^-$
ρ^0	$\rho^0 \to e^+ e^-$		
ω^0	$\omega^0 \to e^+ e^-$		$\omega^0 \to \pi^0\, e^+ e^-$
ϕ^0	$\phi^0 \to e^+ e^-$		$\phi^0 \to \eta\, e^+ e^-$

expressions [10] while the form factors used as well as a discussion on other details can be found for example in [11].

The SHM is very efficient in counting the Lorentz invariant relative yields of different hadrons. This model, however, does not take into account the initial dynamical evolution of the colliding partons from the beam particles. Typically the SHM has been compared with experimental data which has been corrected for the limited acceptance in rapidity and transverse momentum, in which case the initial parton dynamics do not affect the final results. The PHENIX data has not been corrected for the acceptance effects and so in order to be able to compare our calculations with the data, we need to introduce an additional model that correctly accounts for the dynamics not taken into account in the SHM. We wish to do this as simply and transparently as possible so that we do not mask the main physics interest of this paper with complicated dynamical corrections. Thus, both in the longitudinal direction as well as in the transverse direction, we model the initial parton dynamics by simply assuming a two dimensional Gaussian distribution for the momentum distribution of the clusters. Obviously, the means both in rapidity and p_T are zero while we have fitted the widths of the clusters' p_T and y distribution such that the pion distributions become compatible with the measurements.

3. Dielectron production in the LMR in $p + p$ collisions at $\sqrt{s}$=200 GeV

We compare our calculated dielectron invariant mass spectrum with the PHENIX data [1] measured in proton-proton collisions at the top RHIC beam energy in Figure 1. The contributions from the different vector meson decays are shown separately while the thick black line denotes the sum of all relevant contributions. One can see that the model can do a fairly good job in describing the measured data in the LMR and it is clear that the aforementioned details like mass dependent partial widths must be taken carefully into account in order to describe the shape of the data at all invariant masses. We have also added the background contribution from open charm decays (denoted with cc in the figure) but one can see that this contribution is negligible at all invariant masses except between the ω and ϕ meson peaks. We point out here that we have also taken into account the limited experimental mass resolution in the figure by running our calculated curves through a Gaussian smearing filter with a resolution of 10 MeV. This way especially the ϕ meson peak and also the ω peak become broader and compatible with the experimental data.

4. Conclusions

We have demonstrated that an extended statistical hadronization model can describe the dilepton radiation in ultra-relativistic proton-proton collisions at RHIC. In this work, we have implemented the statistical hadronization model including most of the known resonances and thus we have gone beyond the standard hadronic freeze-out cocktail calculations which typically
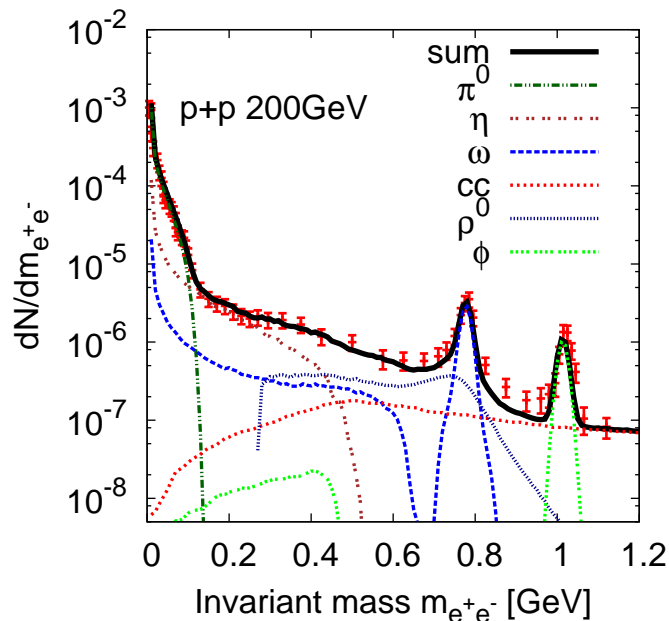
Figure 1. Invariant mass spectrum of correlated pairs of electrons and positrons in proton-proton collisions at $\sqrt{s} = 200$ GeV. The data are from the PHENIX collaboration [1] while the contribution from different dilepton emitting sources are calculated as explained in the text. The full thick black line denotes the sum from all relevant sources.

include only a few different hadron and resonances species whose relative yields are taken either from the experiment or put in by hand. In our approach, the relative yields of different hadron species and thus the relative contribution at different invariant masses of the dielectron spectra is described with only 3 free parameters in the low invariant mass region. Thus, our work underlines the usefulness of the statistical hadronization model since together with simple and intuitive supplementary corrections for the initial state dynamics, we can address not only 4π integrated data but also the differential spectra measured by the PHENIX collaboration.

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