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Dilepton production in pp and CC collisions with HADES

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Abstract. e^+e^- production was studied using the High Acceptance DiElectron Spectrometer (HADES). In pp collisions at 2.2 GeV kinetic beam energy, the exclusive η production and the Dalitz decay $\eta \to \gamma e^+e^-$ have been reconstructed. The electromagnetic form factor of the latter decay was found to be in good agreement with the existing theoretical predictions. In addition, an inclusive e^+e^- invariant-mass spectrum from the $^{12}C + {}^{12}C$ reaction at 2 AGeV is presented and compared with a simplified thermal model.

PACS. 13.25.Jx Decays of other mesons – 13.40.Hq Electromagnetic decays – 14.40.Aq π, K, and η mesons – 25.40.Ve Other reactions above meson production thresholds (energies > 400 MeV)

1 Introduction

One of the main open questions in QCD is the origin of the hadron masses. Beside the so-called Goldstone bosons such as π and η, the typical mass scale of hadrons in the vacuum is in the order of 1 GeV, whereas the current quark masses m_u, m_d are within 5–15 MeV. Based on this fundamental question it has been proposed that the mass of the hadrons is related to the spontaneous breaking of chiral

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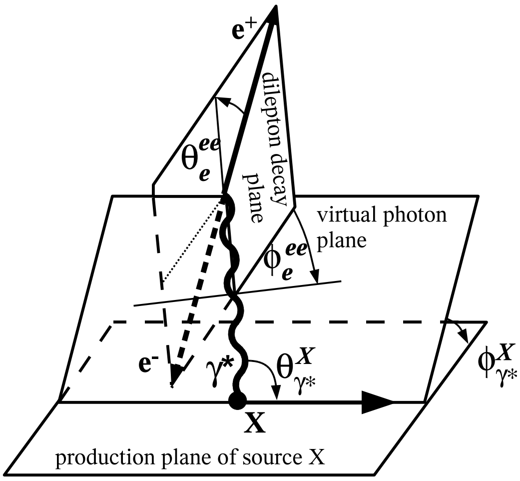

Fig. 1. Overview of the dilepton properties. In addition to the invariant mass $M_{\gamma^*}^{inv}$ and the momentum $P_{\gamma^*}^{X}$, 4 angles have to be taken into account, depending on the production plane and momentum of the source X.

symmetry, which is expected to be partially restored at finite baryon and energy densities. In connection to this question, one of the topics in modern hadron physics is how hadrons behave in strongly interacting matter. This means that their properties —like mass and width— have to be measured inside a cold, dense or hot nuclear environment. In this context, vector mesons have been proposed as an ideal probe for such studies, since they decay via an intermediate virtual photon γ^* into dileptons (e^+e^- or $\mu^+\mu^-$) which do not undergo strong interaction. Recently, the NA60 Collaboration [1] has extracted the ρ spectral function using the dimuon channel in In+In collisions at 158 AGeV, which would correspond to a hot environment. This measurement indicates broadening of the line shape rather than a dropping of the mass.

However, for a complete understanding of the hadronic properties it is important to measure not only the hot, but also the dense region of the phase space. At beam energies of 1–2 AGeV, which correspond to moderate densities (2–3 ρ_0), the production of mesons is dominated by multi-step excitation of a limited number of resonances and their subsequent decays, like $\Delta^{+,0} \to N\pi^0 \to N\gamma e^+e^-$ (π-Dalitz), $\Delta \to Ne^+e^-$ (Δ-Dalitz), $N^*(1535) \to N\eta \to N\gamma e^+e^-$ (η-Dalitz) and the decay of virtual resonances in $N(\omega, \rho)$. Here, most of the production mechanisms are at or even below threshold, which means that mesons are more likely produced in the dense phase of the fireball evolution.

The result of such experiments is usually a dilepton invariant-mass spectrum containing all these sources (dilepton cocktail). Before a conclusion on the properties of ρ and ω can be drawn, the contribution of Dalitz decays has to be evaluated within the detector acceptance and subtracted. In this context, it should be pointed out that a virtual photon (decaying into 2 stable particles) has 6 degrees of freedom, which are outlined in fig. 1: beside the invariant mass $M_{\gamma^*}^{inv}$ these are the momentum $P_{\gamma^*}^{X}$, the polar $\theta_{\gamma^*}^{X}$ and the azimuthal emitting angle $\phi_{\gamma^*}^{X}$ of the virtual photon in the rest frame of the source X. In addition, the 2 decay angles of the photon into dilepton pairs, which are usually described with the helicity angle θ_e^{ee}, and the Treiman-Yang angle ϕ_e^{ee}.

2 The virtual-photon decay properties and the dilepton cocktail

For any interpretation of dilepton invariant-mass spectrum, the decay features of the virtual photons emitted by different sources into the dilepton pair have to be discussed. For the pseudoscalar mesons, which are spin-less, no alignment information can be carried from the production mechanism to the decay, so $\theta_{\gamma^*}^{X}$, $\phi_{\gamma^*}^{X}$ and ϕ_e^{ee} are isotropic. The helicity angle distribution is proposed to be $1 + \cos^2\theta_e^{ee}$ [2]. For a given mass of γ^* its momentum is fixed by the mass of the meson. The only degree of freedom is the mass spectrum, which is based on the electromagnetic form factor [3].

This is very different for the Δ Dalitz decay, because for particles carrying spin, production and decay do not factorize. In addition, the form factor as well as the branching ratio are based on calculations [4] and the helicity angle has quite some uncertainties [2]. For the direct decay of vector mesons, the helicity angle has to be isotropic, but the Treiman-Yang angle could contain higher-order contributions. Moreover, the $\omega \to \pi^0e^+e^-$ transition form factor cannot be consistently described within the Vector Meson Dominance (VMD) model. On the Dalitz decays of the N^* resonances no information is available at all. Therefore, one of the goals of the HADES detector system (installed at GSI, Darmstadt), is to measure the dilepton properties in heavy-ion collisions as well as in elementary reactions. Consequently, the HADES program spans from $p+p$, $\pi+p$ to $\pi+A$ and $A+A$ collisions. First data has been taken in C + C collisions at 1 and 2 AGeV, Ar + KCl collisions at 1.78 AGeV, and $p+p$ at 1.25 and 2.2 GeV. More details on the detector system can be found in [5,6]. Shortly, HADES is a magnetic spectrometer, consisting of up to 4 planes of Mini Drift Chambers (MDC) with a toroidal magnetic field. Particle identification is based on momentum and time-of-flight measurements. In addition, a Ring Imaging Cherenkov detector (RICH) and an electromagnetic Pre-Shower detector (PS) provide lepton identification capabilities.

3 The pp $\to$ ppη reaction at 2.2 GeV

In January 2004 the first pp run has been carried out at a kinetic beam energy of 2.2 GeV, in order to study the performance of the detector using the exclusive reaction $pp \to pp\eta$ which has been measured by the DISTO Collaboration previously [7]. Since the decays $\eta \to \pi^+\pi^-\pi^0$ [8] and $\eta \to \gamma e^+e^-$ [3] are known, they served as a calibration measurement. Moreover, the performance of the HADES setup in extracting electromagnetic form factors has been

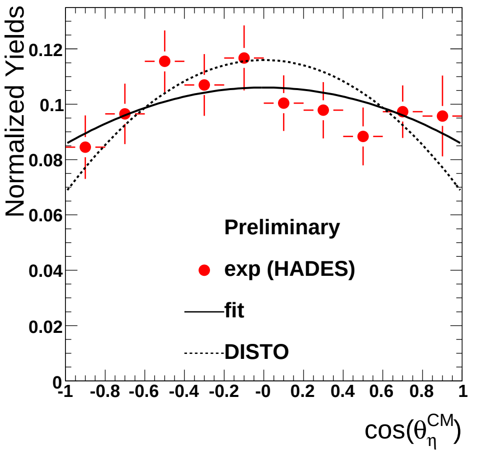

Fig. 2. Distribution of the η polar production angle in the CM frame (statistical errors only, corrected for efficiency and acceptance). The solid line represents a fit to the data, whereas the dashed line shows a parameterization for the existing data [7].

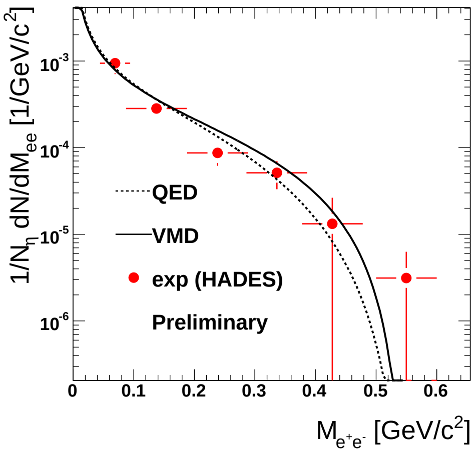

Fig. 3. Invariant-mass distribution M_{ee}^{inv} for the decay $\eta \to \gamma e^+e^-$ [11] (statistical errors only). The dashed line is showing the prediction for a simple QED form factor, while the solid one represents the full VMD calculation [3].

checked. The analysis techniques are described in detail elsewhere [9]. Basically, for both reaction types kinematical constraints were used to identify the missing particle mass of π^0 or γ, respectively. In addition, a kinematic refit reduced the background.

3.1 The hadronic decay $\eta \to \pi^+\pi^-\pi^0$

For the evaluation of the η production, the polar-angle distribution of the η-meson emission has been analyzed. To subtract the background, first a selection on $\cos(\theta_\eta^{CM})$ and a fit on the corresponding *pp* missing-mass spectrum has been done, which resulted in the number of measured η-mesons in intervals of $\cos(\theta_\eta^{CM})$. The extrapolation to the full solid angle has been done using a full Monte Carlo simulation: Events of the type $pp \to pM \to pp\eta$ (with the shape $M \to p\eta$ taken from [7]) have been generated using the Pluto package [10] and processed through the full analysis chain. To evaluate the acceptance and efficiency for each angular interval, the number of reconstructed events has been divided by the number of generated events. Finally, each data point has been corrected by the value obtained by this method.

The result is shown in fig. 2 together with the anisotropy obtained by DISTO with a 2nd-order Legendre coefficient of $c_2 = -0.32 \pm 0.10$. A fit to the data gives $c_2 = -0.14 \pm 0.09$, which tends more to an isotropic η production, but is still consistent within errors with the previous result. This implies that the hadron efficiency is understood as a function of phase space.

3.2 The Dalitz decay $\eta \to \gamma e^+e^-$

Similar methods have been used for the η Dalitz decay. In addition, selecting only events with an opening angle larger than 4°, the contribution of $\eta \to \gamma\gamma$ followed by conversion in the detector material is strongly suppressed. Again, by fitting the *pp* missing-mass spectrum for each invariant-mass slice, the yield has been extracted. For the acceptance correction in this case the measured production angle (as described in the previous section) and the helicity angle (as outlined in sect. 2) have been fixed in the Monto Carlo simulation.

Figure 3 shows the corrected invariant-mass spectrum [11] together with functions using only the form factor from QED as well as the VMD correction [3]. Both curves have been normalized to the total number of measured η's. Since there is a strong dependence on the invariant mass, each data point has been corrected in mass position according to the given statistical mean in each corresponding interval. It can be seen that HADES is not sensitive to distinguish between these 2 models, but the result agrees with both predictions within the errors. This demonstrates that the efficiency is understood as a function of the invariant mass, which is the main important observable in the heavy-ion data. In addition, the ratio between the 2 η decay channels $\left(R = \frac{N_{\eta\to\pi^+\pi^-\pi^0}}{N_{\eta\to\gamma e^+e^-}}\right)$ has been calculated for a full-cocktail simulation and the data. The result is $R_{exp} = 15.3 \pm 1.8_{stat}$ and $R_{sim} = 15.6 \pm 0.9_{stat}$, a nice agreement confirming that the lepton response of the HADES spectrometer is under control [9].

4 Results on C + C at 2 AGeV

The first result on dilepton production in C + C collisions at a kinetic beam energy of 2 AGeV has been published recently [12]. Details of the basic analysis steps can also be found in [13]. Basically, dileptons are identified via the RICH detector and reconstructed using the MDCs. A selection on pairs with opening angles larger then 9° was made in order to suppress the backgroung from γ conversion. The combinatorial background (*i.e.*,

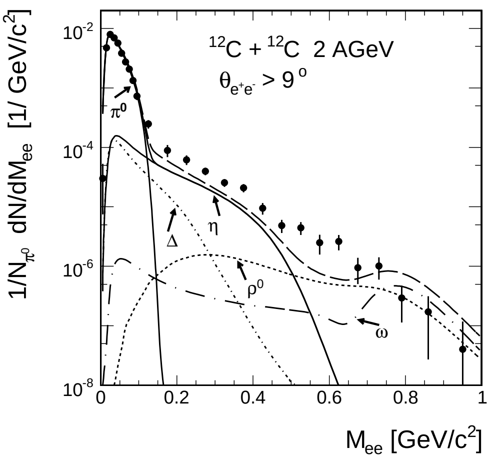

Fig. 4. Invariant-mass distribution M_{ee}^{inv} for CC at 2 AGeV [13]. The data points contain statistical error only. The lines are a thermal-model simulation as described in the text.

pairs mixed from different sources) has been removed by means of the like-sign method, where the number $N_{CB} = 2\sqrt{N_{++}N_{--}}$ has been obtained by forming pairs with equal charge in the same event. For events with masses ($M_{ee}^{inv} > 0.5\,\mathrm{GeV}/c^2$) the combinatorial background has been evaluated using the event-mixing technique. Here, opposite-sign pairs have been formed from different events but the same target segment.

In contrast to exclusive reactions, heavy-ion reactions depict only the final dilepton cocktail, without any selection on the different sources. As explained above, the virtual-photon properties might vary, thus the extrapolation to 4π is difficult, since 6 independent variables should be taken into account. While the integration over these variables cannot be done, a different method has been chosen. To allow for a model-independent comparison to our data, a single-track efficiency as a function of $p_e^{lab}, \theta_e^{lab}, \phi_e^{lab}$ has been extracted by simulation and applied to each lepton track, and finally combined to a dilepton efficiency. No attempt has been made to correct the resulting dilepton spectra for the geometrical acceptance. This was taken into account by a matrix using the same parameters per track for acceptance filtering of the models [14]. Figure 4 shows the invariant-mass spectrum after all analysis steps. Absolute normalization has been done by means of the measured charged pions, whose average value is the expected number of π^0 in an isospin-symmetric reaction.

In order to account for the contribution from the known Dalitz decays of the pseudoscalar mesons, a simulation has been made based on a simple thermal model [10] and filtered with the detector acceptance matrix as described above. The resulting curves are shown in fig. 4 as well. The solid line contains the π and η Dalitz decays with the decay properties as already mentioned and the known production cross-sections and distribution from TAPS [15]. It can be seen, that the π^0 region is well described, however, already in the η region model and data disagree. It is clear that additional sources are needed.

For a more complete view, Δ production has been added by π^0 scaling and the vector meson production by m_T scaling [16]. Still a factor of around 2 remains unaccounted for in the mass region of $0.2\,\mathrm{GeV}/c^2 < M_{ee}^{inv} < 0.7\,\mathrm{GeV}/c^2$, where the Δ decay is part of the contribution, as well as the low-mass tail of the ρ-meson. It has to be clarified if this enhancement is due to a different Δ yield and/or decay properties, or modified vector meson shapes in the dense medium. This means that the HADES data has to be compared to advanced model calculations [17–19], which, on the other hand, need more constraints extracted by elementary collisions. In this context, the decay properties of the virtual photon play an important role.

5 Summary and outlook

In summary, results for dilepton production obtained with HADES in elementary as well as in heavy-ion collisions have been presented. While the analysis of data sets, briefly described in this work, is almost finished, the CC collision at 1 AGeV is under analysis. In addition, a *pp* run at 1.25 GeV (below the η threshold) dedicated to Δ production has allowed us to collect promising statistics in spring 2006. Systematic studies using elementary reactions will continue, which are of particular importance for the interpretation of the inclusive invariant-mass spectra in heavy-ion collisions.

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