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Characterising the hot and dense fireball with virtual photons at HADES

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Electromagnetic probes (γ, γ^*) offer a unique opportunity to study the conditions during heavy-ion collisions. They are produced throughout the whole evolution of the colliding system and can penetrate the strongly interacting medium to bring direct information from their origins to the detector. In this manner, it is possible to not only probe freeze-out, but also earlier stages where maximum temperature and density are produced.

We present measurements of dielectrons from Ag+Ag collisions, collected with the High-Acceptance-DiElectron-Spectrometer (HADES), at $\sqrt{s_{NN}} = 2.55$ GeV and $\sqrt{s_{NN}} = 2.42$ GeV. A particular focus is set on collectivity studies with a multidifferential analysis of the directed flow v_1 and elliptic flow v_2 in terms of centrality, rapidity, transverse momentum and invariant mass.

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1. Introduction

The High-Acceptance-Di-Electron-Spectrometer (HADES) at GSI, Darmstadt, is a fixed target experiment designed to investigate heavy-ion collisions at a few GeV energy regime. As such, it probes the QCD phase diagram at high net-baryon densities and moderate temperatures, similar to conditions present in neutron star mergers [1]. Here, as well as throughout higher collisions energies, the measurement of virtual photons provides a unique window into the conditions of the system during early phases of highest temperature and density. Since such electromagnetic probes are created throughout its evolution, however, it is necessary to isolate the contribution of interest. In addition, these rare probes with branching ratios down to the order of 10^{-5} require a data set with accordingly large number of recorded events.

In this analysis, HADES measurements from Ag+Ag collisions at center-of-mass energies of $\sqrt{s_{NN}} = 2.42$ GeV and $\sqrt{s_{NN}} = 2.55$ GeV are studied. With an accepted trigger rate of about 16 kHz and four weeks of beam time, they provide a pool of around 9 billion events to serve as the basis for the following work.

2. Particle Identification

The HADES consists out of several distinct detector components which are combined to allow for a full reconstruction of charged particles [2]. First, the diamond-based START detector acts as beam monitoring tool and provides a start time for incoming ion bunches. After a collision occurs inside the target, the trajectory of produced particles is reconstructed using a first set of Multiwire-Drift-Chambers (MDC). Then, a superconducting toroidal magnet, with maximum field values of $B = 3.6$ T [3], is combined with a second set of MDCs to measure the particles deflection from their original tracks. A final set of detector arrays in form of Resistive-Plate-Chambers (RPC) at $\theta < 45°$ and scintilallor detectors (TOF) at $\theta > 45°$ provide a time-of-flight. All in all, this setup covers almost full azimuthal angle, as well as large polar angles between 18° and 85°, while providing the necessary information to reconstruct each particle's mass to charge ratio. Energy loss information from the MDCs and TOF can be utilised to further separate light nuclei.

Apart from this kinematic reconstruction, an independent Ring-Imaging-Cherenkov (RICH) detector is placed around the target. It is designed to emit Cherenkov radiation when and only when electrons or positrons pass through its radiator gas volume. The emitted photons are then reflected on a spherical mirror and detected by an array of photon detectors. With an upgrade of this array shortly before the run in 2019, the performance of the RICH detector has drastically increased compared to previous HADES experiments [3].

In the end, leptons are identified via their relatively high velocity around $\beta = 1$ and a matching signal in the RICH detector. Figure 1 demonstrates how the purity stays above 90% throughout the full momentum range, while maintaining a reconstruction efficiency in the order of 60%.

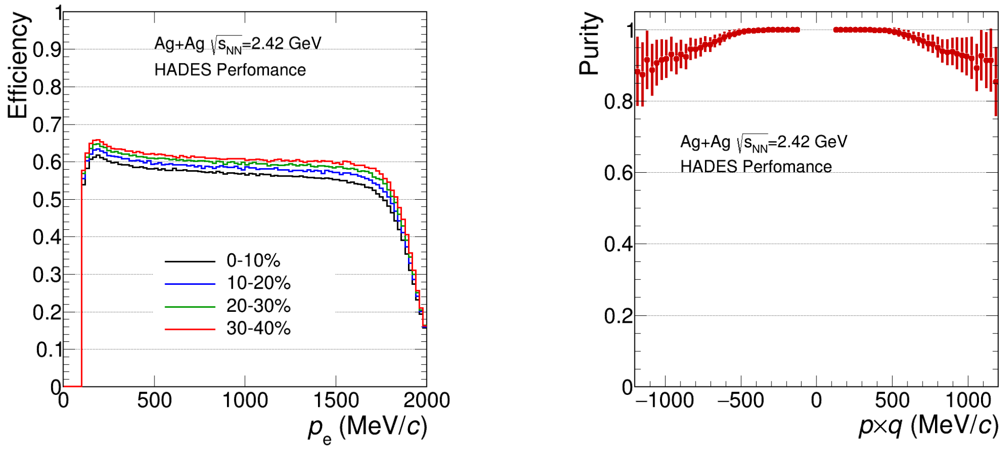

Figure 1: Left panel: Estimated efficiency for the reconstruction and identification of electrons hitting the detector. Right panel: Estimated purity of identified electrons/positrons. Vertical lines represent statistical uncertainties.

At last, a Forward-Hodoscope-Wall (FW) is placed seven meters behind the target, covering small theta angles around $0.33° < \theta < 7.17°$. This allows measurements of spectator fragments and can be utilised to reconstruct the event plane, see section 4. It also provides one method to estimate collisions centralities.

3. Extraction of Dilepton Signal

After the selection of individual electrons and positrons, the actual dilepton signal is identified indirectly. For this purpose, all possible e^+ and e^- combinations are matched, introducing a combinatorial background N_{CB} that needs to be subtracted. The latter can be estimated via the geometric mean of like-sign pairs N_{++}^{SE} and N_{--}^{SE} [1]:

$$N_{CB}^{SE} = 2k\sqrt{N_{++}^{SE} \cdot N_{--}^{SE}} \tag{1}$$

Here, the factor k is introduced to correct for differences in acceptance between electrons and positrons. Alternatively, it is also possible to estimate N_{CB} by matching individual leptons with a partner from a different event. Although this does not describe any correlations, as they are known to be present from Dalitz decays, this event-mixing method allows for virtually unlimited statistics, reducing statistical uncertainties in the background estimation. Consequently, it is especially useful at the higher invariant masses where uncorrelated background dominates and the relative statistical uncertainties increases with fewer counts. The resulting dilepton signal is seen in figure 2, where the combinatorial background is based on N_{CB}^{SE} up to 300 MeV$/c^2$. Beyond 300 MeV$/c^2$ event-mixing is applied to estimate N_{CB}.

This signal serves as an integral over the whole evolution of the collision. Various decay channels contribute to the spectrum, yet for this analysis the main interest lies in the thermal dilepton yield from the hottest and densest stage. Therefore, figure 3 shows the measured dilepton spectrum in comparison to PLUTO [4] simulations of freeze-out sources, i.e. η, π^0 and ω mesons.

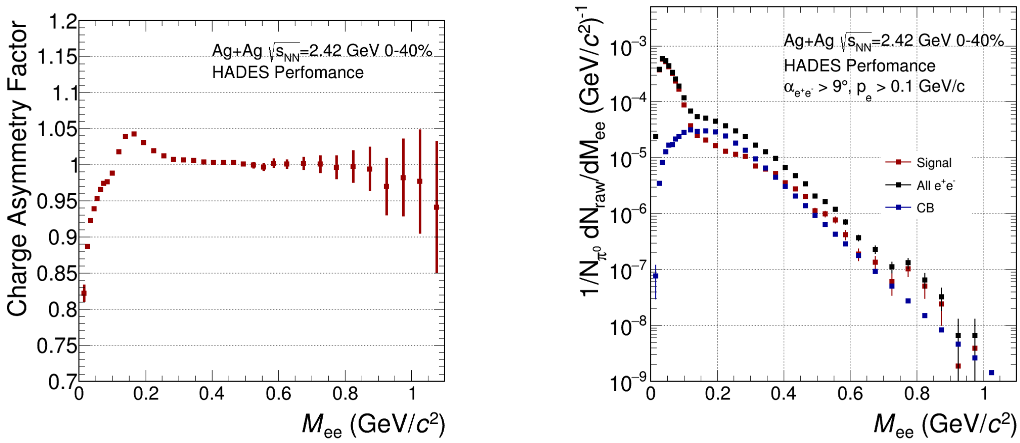

Figure 2: Left panel: Charge asymmetry factor k as function of invariant mass. Right panel: Invariant mass distribution of all e^+e^- (black square), combinatorial background (blue square) and signal (red square). Vertical lines represent statistical uncertainties.

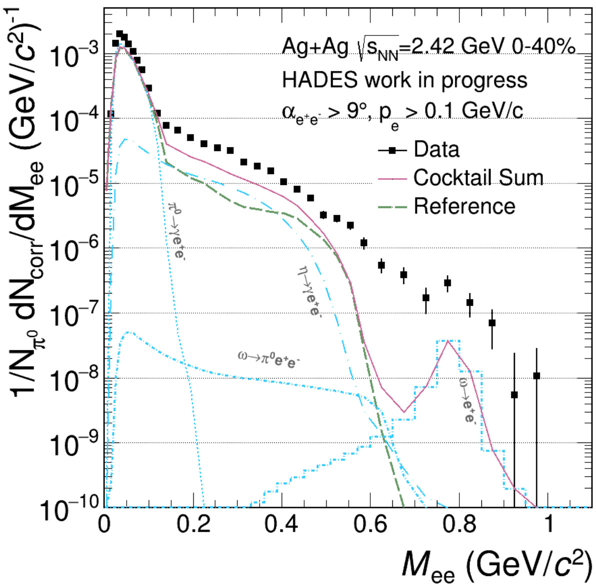

Figure 3: Efficiency corrected signal in comparison with Pluto cocktail for Ag+Ag collisions, 0-40% centrality, at $\sqrt{s_{NN}} = 2.42$ GeV. The cocktail sum consists out of the η, ω signal as well as the signal from elementary pp and np collisions. The latter has been measured at the same energy of $\sqrt{s_{NN}} = 2.42$ GeV. Vertical lines represent statistical uncertainties.

A measurement from nucleon-nucleon collisions further serves as a reference and describes the initial Nucleon-Nucleon contributions to the spectrum. In figure 3, a clear excess over the the cocktail, associated with the thermal in-medium ρ contribution, is visible. Ongoing work is performed to isolate this excess, which will allow insights into the temperature and lifetime of the fireball stage.

4. Anisotropic Flow Analysis

Anisotropies in the particles azimuthal distribution are proposed to be another observable sensitive to the earlier stages of the collision. Let Ψ_{RP} be the angle of the reaction plane, one can mathematically describe the magnitude of anisotropy via the Fourier series:

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n\Delta\phi \qquad \text{with} \quad \Delta\phi = \phi - \Psi_{RP} \tag{2}$$

where v_n are the flow coefficients. For this analysis, a focus is set on the directed flow v_1 and elliptic flow v_2. After the estimation of the event plane, with the information provided by the Forward Wall, one can directly characterise the dilepton anisotropy with equation 2. The resulting elliptic flow of dileptons, measured in dependence of the invariant mass, is depicted in figure 4. As expected from the estimated cocktail in figure 3, the low mass range is dominated by e^+e^- from Dalitz decays of pions, and thus follows their negative flow due to squeeze-out effects. However, with increasing invariant mass, the dilepton v_2 aligns more closely with zero, deviating from other measurements of elliptic flow in freeze-out hadrons. This is true even when considering the statistical and systematic uncertainties. It is, hence, an indication of the penetrating nature of thermal dileptons, which seem to be created before the collective flow has fully built up. In order to investigate this behavior in more detail, a more multidifferential study, looking also at transverse momentum, rapidity and centrality dependence is currently ongoing.

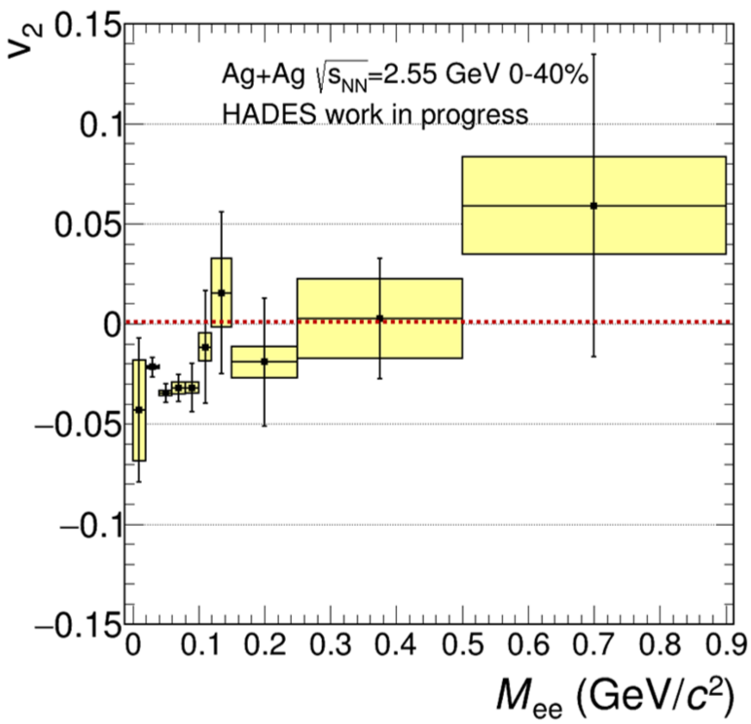

Figure 4: Elliptic flow v_2 in dependence of invariant mass M_{ee}. Vertical lines represent statistical uncertainties. Boxes represent systematic uncertainties, see text below for more details.

At the moment, the systematic uncertainties are mainly estimated based on different treatments of the combinatorial background, the efficiency correction as well as by varying methods to calculate the dilepton flow coefficients. Potential biases and uncertainties due to the lepton selection are still under investigation.

5. Summary and Outlook

The Ag+Ag collisions $\sqrt{s_{NN}}$ = 2.42 GeV and $\sqrt{s_{NN}}$ = 2.55 GeV, measured at HADES in 2019, provide a unique opportunity to study the conditions in the fireball during the earliest stages. Over a million dileptons have been reconstructed, which are now analysed in terms of not only invariant mass spectra, but also in terms of anisotropic flow. In this regard, the reconstructed elliptic flow for higher invariant masses, suggests small, if any, flow experienced by dileptons at the early stages. Ongoing work is performed to look at this relevant mass range more multidifferentially, i.e. in dependence of transverse momentum, rapidity as well as centrality. Measurements of the π^0, and ideally η, flow via separate decay channels will, in addition, allow a direct subtraction of their contribution to the integrated spectrum. In this way, the goal is to isolate the thermal dilepton flow.

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