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Characterising the hot and dense fireball with virtual photons at HADES

Niklas Schild[a,*] **for the HADES Collaboration**

[a] *Technische Universität Darmstadt,*
Karolinenplatz 5, 64289 Darmstadt, Germany

E-mail: `n.schild@gsi.de`

Electromagnetic probes (γ, γ^*) offer a unique opportunity to study the conditions in heavy-ion collisions throughout their whole evolution. Once created, these particles can travel largely unhindered through the strongly interacting medium and bring direct information from their origins to a detector. Virtual photons, decaying into lepton pairs, serve as particularly interesting because they also carry additional information encoded in their invariant mass.

In this contribution, work-in-progress measurements of such dileptons are presented. Based on high statistics experiments of Au+Au and Ag+Ag collisions, collected with the High-Acceptance-DiElectron-Spectrometer (HADES), at center-of-mass energy of $\sqrt{s_{NN}} = 2.42$ GeV and $\sqrt{s_{NN}} = 2.55$ GeV respectively, various dilepton observables can be extracted. This includes the invariant mass spectra, allowing a determination of the in-medium spectral functions, fireball temperature as well as the overall dilepton yield, which can be connected to the lifetime of the fireball. Furthermore, first work-in-progress results on the dilepton anisotropic flow coefficients are presented, giving more insights into the collective properties of the hot and dense medium.

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1. Introduction

The High-Acceptance-DiElectron-Spectrometer (HADES) [1], at GSI in Darmstadt, provides a unique opportunity to study the conditions in heavy-ion collisions in an energy regime of a few GeV per nucleon. The hottest and densest stage in such collisions is characterised by densities 2-3 times above groundstate and medium temperatures of about 70 MeV. In this way, it represents similar conditions as are present in neutron star mergers [2].

2. Particle Reconstruction and Identification

Electrons and positrons serve as the lightest charged particles emerging from the collision, a fact which is exploited at HADES in a number of selection criteria to separate these rare probes from the more abundantly produced hadrons. First, this includes information from a Ring-Imaging-Cherenkov-Detector which is designed to emit Cherenkov radiation when electrons or positrons pass through its radiator gas chamber. The emitted photons are then reflected on a spherical mirror and detected by an array of photon detectors. Second, two pairs of Multiwire-Drift-Chambers (MDCs) and a superconducting toroidal magnet allow for the reconstruction of the particles track as well as momentum. Third, an array of META (Multiplicity Electron Trigger Array) detectors, located behind the last set of MDCs, is used to determine the time-of-flight, and thereby the particles velocity. Fourth, since 2018 a newly installed detector layer with an electromagnetic spectrometer (ECAL) allows direct detection of photons and provides additional information to separate electrons from pions. Fifth and finally, the forward wall hodoscope, covering polar angles of $0.3^\circ < \Theta < 7.17^\circ$ [4] can be used to reconstruct the event plane and collision centrality through the detection of spectators.

In the end, all information from the different detector sub-systems is combined in order to reconstruct every particles track as well as their characteristics in terms of mass, momentum, charge etc. Further, leptons are identified based on their corresponding signal in the RICH detector and their relatively high velocity compared to the heavier hadrons. A final improvement towards a high purity of the sample is made by generating the selection criteria momentum-dependent.

3. Reconstruction of the Invariant Mass Spectrum

The combinatorial background N_{CB}^{SE}, stemming from the combination of individual electrons and positrons into e^+e^- pairs, is estimated as the geometric mean of like-sign pairs N_{++}^{SE} and N_{--}^{SE} [2]:

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

where k is introduced as an additional factor to incorporate differences in acceptance and efficiency experienced by positively versus negatively charged leptons. It is calculated based on event-mixing techniques:

$$k = \frac{N_{+-}^{mix}}{\sqrt{N_{++}^{mix} N_{--}^{mix}}} \tag{2}$$

The k-factor is shown in figure 1 (left panel) as a function of invariant mass. One can note how k converges to unity for higher mass ranges. The resulting signal, after subtraction of the combinatorial background, is shown on the right panel of figure 1.

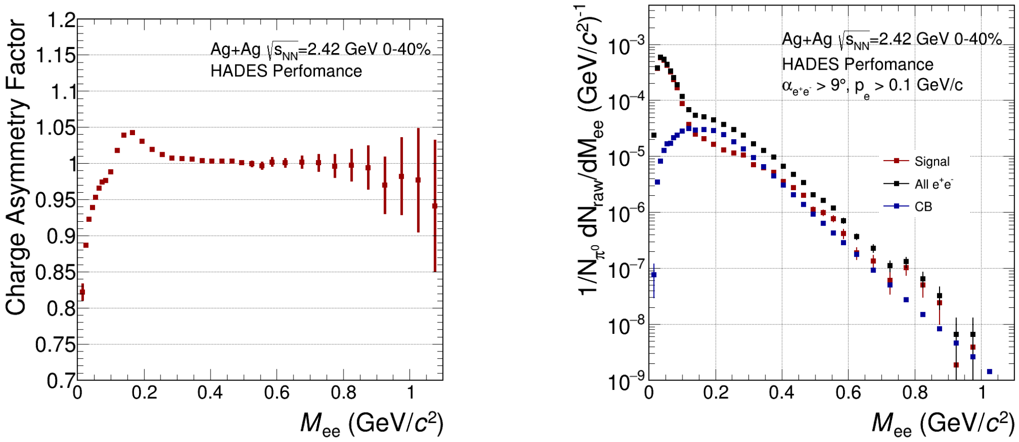

Figure 1: Left panel: Charge asymmetry factor k as function of invariant mass. Right panel: Invariant mass distribution of all e^+e^- (black square), combinatorial background (blue square) and signal (red square) (Ag+Ag 0-40% centrality at $\sqrt{s_{NN}}$ = 2.42 GeV, HADES). Vertical lines represent statistical uncertainties.

In order to estimate the efficiency losses due to imperfect track reconstruction and particle identification, simulated electrons/positrons are embedded into experimental data. Their detector response is imitated via GEANT [3] such that they can undergo the same selection procedure.

In this way, the acceptance ϵ_{acc} is given by the total number of simulated input particles $N_{4\pi}$ over the particles in acceptance N_{acc}, while the efficiency ϵ_{eff} is given by the number of reconstructed particles N_{rec} which remained in the sample after the selection procedure:

$$\epsilon_{acc} = \frac{N_{acc}}{N_{4\pi}} \qquad\qquad \epsilon_{eff} = \frac{N_{rec}}{N_{acc}} \tag{3}$$

As one can see on the left panel of figure 2, the applied selection criteria translate to an efficiency of about 60%, largely independent of the momentum and with a slight (2%) difference between centrality classes. Furthermore, the right panel of figure 2 shows the efficiency corrected invariant mass spectrum with a simulation of its cocktail contributions as well as a measurement of the nucleon-nucleon reference (NN reference). A clear excess is visible over the cocktail. It is associated with the thermal in-medium ρ contribution and will be isolated from the data by subtracting the dominant sources, i.e. the η contribution and the NN Reference.

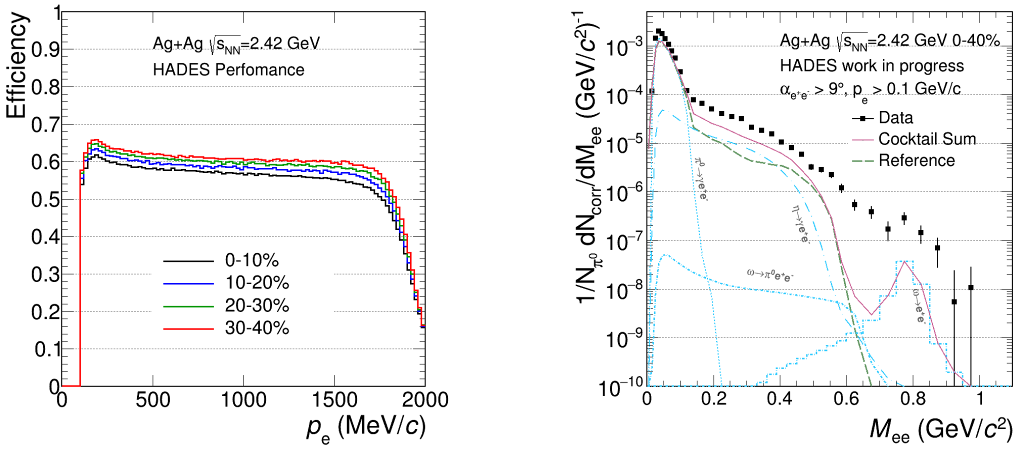

Figure 2: Efficiency corrected signal in comparison with Pluto cocktail for Ag+Ag collisions, 0-40% centrality, at $\sqrt{s_{NN}} = 2.42$ GeV. The cocktail sum consists out of the η, ω signal as well as the signal from elementary pp and np collisions. The latter has been measured at 1.23A GeV. Vertical lines represent statistical uncertainties.

After isolation of the excess spectrum, ongoing work is done to extract some key observables. First, the excess yield, measured in the dominant ρ-region of $0.3 < M_{ee}(\mathrm{GeV}/c^2) < 0.7$, is connected to the lifetime of the fireball. Second, the thermal nature of the excess dileptons translates to a temperature-regulated slope in the invariant mass spectrum. Therefore, the fireball temperature T may be determined via a Boltzman fit assuming black body radiation [2]:

$$\frac{dN}{dM} \propto M^{\frac{3}{2}} \exp(-M/T) \tag{4}$$

4. Anisotropic Flow Analysis

In addition to the reconstruction of the invariant mass spectrum, the high-statistics data of Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV allows for further studies in terms of collective observables. In particular, first efforts have been made to determine the anisotropic flow coefficients v_1, referred to as directed flow, and v_2, referred to as elliptic flow. If Ψ_{RP} is the angle of the reaction plane and ϕ the azimuthal angle, they are mathematically defined by the Fourier series:

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n\Delta\phi \qquad \text{with} \quad \Delta\phi = \phi - \Psi_{RP} \tag{5}$$

Therefore, the distribution of $\frac{dN}{d\Delta\phi}$ is reconstructed as in the left panel of figure 3 and fitted with equation 5, in this case up to second order. The resulting elliptic flow v_2 is shown in the right panel. It shows negative flow values due to pion contribution at low masses, and appears to be consistent with zero at higher masses.

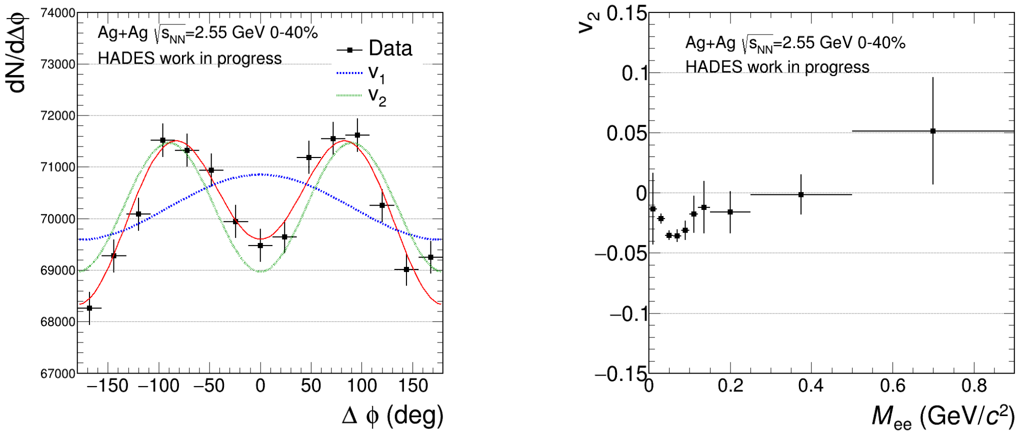

Figure 3: Left panel: $\frac{dN}{d\Delta\phi}$ distribution. Red line represents total fit, while green and blue line show contribution from first and second order flow coefficients. Right panel: Extracted elliptic flow v_2 in dependence of invariant mass M_{ee}. Vertical lines represent statistical uncertainties.

5. Outlook

This analysis aims to reconstruct the invariant mass distribution of dileptons in Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.42 GeV. This will allow a comparison with existing HADES data of Au+Au collision at the same collision energy, thereby giving insights not only into centrality, but also the overall system size dependence of the dilepton excess.

An additional goal is the multidifferential measurement of directed and elliptic flow coefficients. For this purpose, systematic uncertainties are in the process of being evaluated. Furthermore, the thermal contribution is to be isolated from freeze-out contributions by subtraction of measured flow coefficients of pions and eta mesons.

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