Studying properties of baryon-dominated matter with di-leptons

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Abstract. Virtual photons (γ^*) are an excellent tool to investigate strong-interaction matter under extreme conditions. Their penetrating nature not only enables the study of bulk properties of such a medium (e.g. temperature measurements unbiased by the collective expansion of the fireball) but also an insight to the microscopic structure of matter. The HADES experiment has measured virtual photons in their di-electron decay channel in heavy-ion collisions as well as in proton- and pion-induced reactions in the center-of-mass energy range of a few GeV. In this contribution, we emphasize multi-differential spectra and collective behavior of di-lepton sources in Au+Au collisions at $\sqrt{s_{NN}}$ = 2.42 GeV and Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.55 and 2.42 GeV and contrast them with hadronic probes at the freeze-out stage.

1 Introduction

Heavy-ion experiments at a few GeV collision energies provide a unique opportunity to study nuclear matter at high densities around $2-3$ times the saturation density ρ_0, and at high temperatures of tens to a hundred MeV/k_b. The understanding of strongly interacting, baryon-dominated matter in this region is crucial for the full exploration of the QCD phase diagram and has direct connections to astrophysical observables, in particular neutron stars and neutron star mergers.

Electromagnetic probes (γ, γ^*) serve as one of the promising tools to study these collisions experimentally. They allow direct investigations of the collision system not only at freeze-out, but in its whole evolution and in particular during the hottest and densest stage, referred to as the fireball. This is because they do not interact via the strong interaction, which allows them to escape the medium largely undisturbed. In addition, virtual photons decaying into di-lepton pairs carry additional information within their invariant mass.

2 Experimental Setup

The High-Acceptance-Di-Electron-Spectrometer (HADES) is a fixed target experiment at GSI in Darmstadt, operated using the SIS18 accelerator. It is characterized by a large acceptance with a coverage of 18°-85° in the polar angle θ and virtually the full 0°-360° in the azimuthal angle ϕ. In addition, it is designed specifically for high-statistics measurements of virtual photons via dedicated detector components for the identification of electrons and a low material budget in the tracking system. A full technical description can be found under [1].

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In this work, we mainly focus on heavy-ion collisions of Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV and Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 and 2.42 GeV, recorded with HADES in 2012 and 2019. The collected statistics enable us to perform a multi-differential analysis of di-leptons for varying energies and collision systems. Furthermore, the full azimuthal coverage and usage of a forward detector allow, for the first time, for a reconstruction of their azimuthal anisotropy, see section 4.

3 Reconstruction of the Di-Electron Spectrum

Figure 2 (left panel) shows an example of the reconstructed di-electron signal, as it has been measured within the HADES acceptance for Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.42 GeV. Such a measurement represents an integral of all di-electron contributions over the full evolution of the system.

To isolate the thermal contribution emitted from the hot and dense fireball, the subtraction of freeze-out sources as well of contributions from first-chance N+N collisions is necessary.

In this case, $p+p$ and $p+n$ contributions have been measured and reconstructed at the same energy of $\sqrt{s_{NN}}$ = 2.42 GeV. This provides a reference measurement for di-lepton contributions from isolated N+N collisions, which serves as a proxy for the initial stage radiation. For the second energy of $\sqrt{s_{NN}}$ = 2.55 GeV, such $p+p$ reactions have also been recorded. The dataset is under analysis and will provide the necessary baseline for the Ag+Ag data [2]. Figure 1 shows a fair agreement between the measured data and theory predictions from the GiBUU model. Small deviations at lower masses are under investigation.

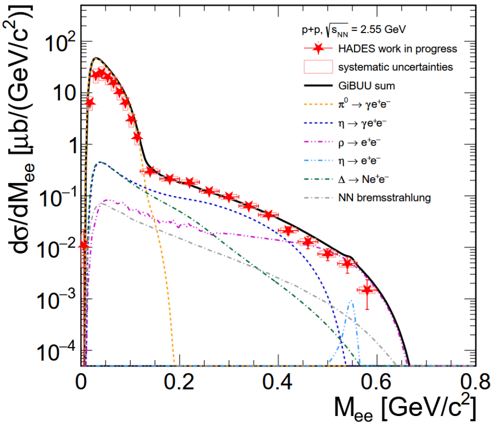

Figure 1. Invariant mass distribution from p+p collisions at $\sqrt{s_{NN}}$ = 2.55 GeV in comparison to a GiBUU simulation within HADES acceptance.

Furthermore, the freeze-out part of the cocktail, containing mainly contributions from π^0 and η Dalitz decays, are estimated via the analysis of other decay channels. All contributions are then added together into a cocktail sum which represents the non-thermal di-electron sources. The remaining difference to the data is assumed to come from thermal radiation. It can therefore be isolated simply by subtraction of the cocktail sum. The resulting thermal excess is shown in the right panel of figure 2. Note that the data has also been extrapolated to the full phase space using realistic simulations.

Several important characteristics can be extracted. For one, the data shows a nearly exponential shape which can been fitted to extract a temperature k_bT. It can be understood as the average fireball temperature and demonstrates the penetrating nature of di-leptons [6]. For another, the excess yield, describing how many thermal di-leptons have been emitted during the lifetime τ of the fireball, can be calculated. It is of high interest, especially in comparison and with combination of additional measurements, because it is expected to be depend monotonically to τ. Finally, first model comparisons show a fair agreement with coarse-grained simulations [5] using medium-modified spectral functions, which should help to better understand the origin of the thermal radiation and disentangle thermal from non-thermal contributions [7].

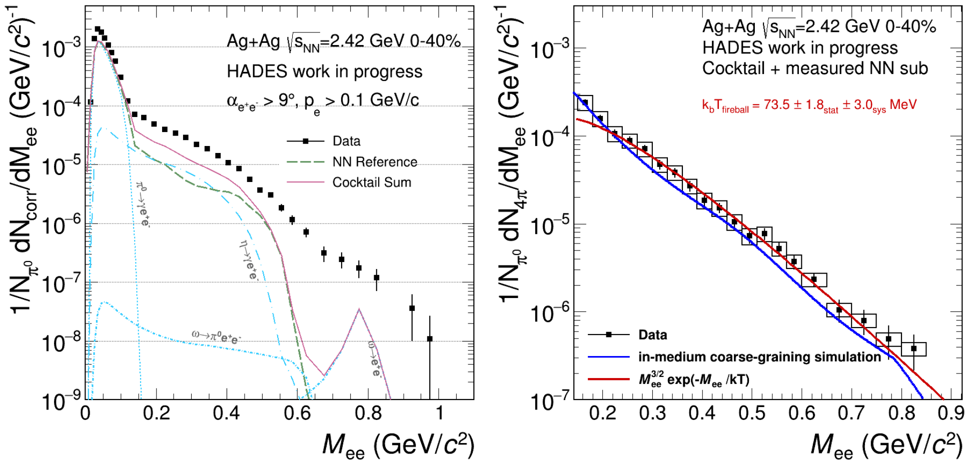

Figure 2. Left panel: Invariant mass spectrum within HADES acceptance. Black points show measured data with statistical uncertainties. Light blue lines show various contributions to the overall di-lepton signal as simulated via Pluto. The green line shows the measured reference from $p + p$ and $p + n$ collisions at the same energy [3]. The remaining difference between the freeze-out cocktail sum and signal is attributed to thermal radiation. [4]
Right panel: Thermal Excess Spectrum. Black points show measured data with statistical uncertainties. Boxes represent systematic uncertainties. The curve shows good agreement with coarse-grained calculations [5]. An exponential fit allows for the extraction of a fireball temperature k_bT.

The same procedure is performed also for Au+Au collisions at the same energy, as well as Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.55 GeV. Together, this enables the systematic study of the thermal excess for varying energies and systems. This is further extended to a differential analysis in terms of centrality and will provide a unique opportunity to study the complex relationship between the excess yield, fireball temperature, fireball lifetime and the volume of the system.

4 Collectivity Studies

By virtue of their penetrating nature, the study of further observables with di-leptons, beyond the invariant mass spectrum, is of high interest. In this work, one important aspect are collective properties, in particular the collective flow and azimuthal anisotropy. As discussed in the previous section, the thermal radiation can probe the system during the hottest and densest stage before freeze-out. Thus, a di-electron measurement may track the evolution of the azimuthal anisotropy over time, which is particularly interesting at collision energies of a few GeV due to squeeze out effect. Here, we focus on the directed flow v_1 and elliptic flow v_2. Figure 3 shows an example of the integrated ellitpic flow measurement for the highest statistics measurement of Ag+Ag at $\sqrt{s_{NN}}$ = 2.55 GeV. This signal represents an integral over time and entails both thermal and non-thermal sources. In this case, a major contribution comes from the π^0 Dalitz decay. They experience an overall negative v_2 because of the shadowing of in-plane emission due to interplay with spectators at these collision energies.

An extension of this result, involving the isolation of the purely thermal signal, is under preparation. Precise knowledge of both the strength of the elliptic flow v_2 and the relative yields for each freeze-out source is required. This can be accomplished ideally with additional measurements. At the same time, while a precise description of the yield is not yet

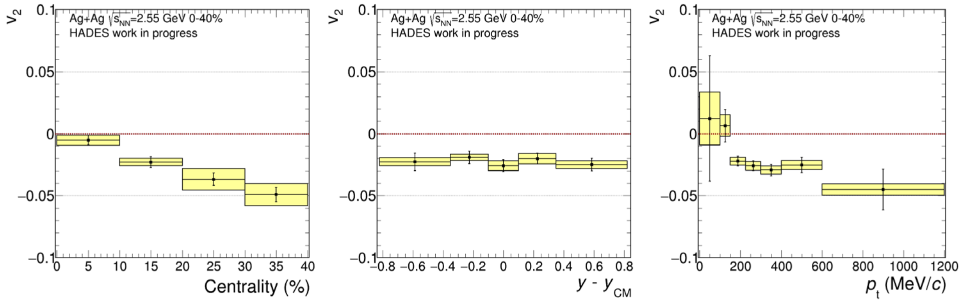

Figure 3. Differential measurements of the integrated di-electron v_2 in dependence of the centrality (left panel), rapidity (middle panel) and transverse momentum (right panel) for Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV. Vertical lines represent statiscal uncertainties. Boxes represent systematic uncertainties.

available, the comparison of transport model predictions with existing charged pion data has shown promising agreement in terms of the azimuthal anisotropy [8]. Therefore, by combining experimentally estimated yields with flow parameters from transport models, the contribution of neutral mesons can be subtracted. A detailed investigation is currently ongoing. First results indicate that the thermally dominated di-electron signal shows smaller, or even positive, v_2 in comparison to the freeze-out sources [9].

5 Summary and Outlook

We have presented work-in-progress results of di-electron measurements from Au+Au collisions at $\sqrt{s_{NN}} = 2.42$ GeV and Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ and 2.42 GeV recorded at HADES. One focus is set on to the isolation of the thermal excess, which is performed for each system to be studied multi-differentially. In addition, the flow coefficients of the integrated di-electron signal have been reconstructed. Ongoing efforts are made to isolate the thermal di-electron ellitpic flow in order to probe the time evolution of the systems in terms of azimuthal anisotropy.

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