Dilepton production and resonance properties within a new hadronic transport approach in the context of the GSI-HADES experimental data

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The dilepton emission in heavy-ion reactions at low beam energies is examined within a hadronic transport approach. In this article the production of electron-positron pairs from a new approach named SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) is introduced. The dilepton emission is consistently taken into account below the hadronic threshold. The calculations are systematically confronted with HADES data in the kinetic energy range of $1 - 3.5\, \text{A GeV}$ for elementary, proton-nucleus and nucleus-nucleus reactions. The present approach employing a resonance treatment based on vacuum properties is validated by an excellent agreement with experimental data up to system sizes of carbon-carbon collisions. After establishing this well-understood baseline in elementary and small systems, the significance of medium effects is investigated with a coarse-graining approach based on the same hadronic evolution. The effect of explicit in-medium modifications to the vector meson spectral functions is important for dilepton invariant mass spectra in ArKCl and larger systems, even though the transport approach with vacuum properties reveals similar features due the coupling to baryonic resonance and the intrinsically included collisional broadening. This article provides a comprehensive comparison of our calculations with published dielectron results from the HADES collaboration. In addition, the emission of dileptons is predicted in gold-gold and pion-beam experiments for which results are expected soon.

I. INTRODUCTION

Dileptons are a clean probe for hot and dense matter under extreme conditions, as it is studied in heavy-ion collisions in a wide range of beam energies. Since they only interact electromagnetically, they escape the medium nearly unperturbed. Therefore, they allow unique access to the properties of the medium and resonances that decay within a strongly interacting medium. In contrast, hadronic decay products suffer from rescattering and absorption such that the interesting information about the hot and dense stage of the reaction is masked.

More specifically, dilepton production offers a complementary perspective on the spectral function of the vector mesons, which is reflected in the invariant mass spectrum of the lepton pairs. A modification of these spectral functions might indicate the restoration of chiral symmetry [1,3]. Chiral symmetry is of major interest to research, since its breaking accounts to a large extent for the mass generation of the visible matter [4]. The corresponding modifications to the spectral function of vector mesons inside a hot and dense medium have been discussed in the literature [5-7]. Especially, NA60 results for dimuon spectra favor a broadening of the spectral function of the $\rho$ meson [8,9]. For example, calculations based on hadronic many-body theory [10] and the functional renormalization group [11] are performed to obtain a quantitative understanding of this effect.

This work focuses on the dilepton production in elementary, nucleon-nucleus and nucleus-nucleus collisions. Experimentally, the emission of dielectrons or dimuons was studied at a number of different facilities. At CERN SPS the high quality experimental data from NA60 [9] allowed investigation of the $\rho$ spectral function and confirmed the previous dilepton measurement from CERES [12] that revealed an excess in the intermediate invariant mass region. For higher energies up to $\sqrt{s_{NN}} = 200\, \text{GeV}$ dileptons are measured at RHIC by STAR [13] and PHENIX [14]. Both also report an enhancement in the dilepton invariant mass range from 0.30 to 0.76 GeV that is attributed to a broadening of the $\rho$ spectral function. The present work focuses on the dielectron production in the kinematic regime of low beam energies ($E_{\text{Kin}} = 1 - 3.5\, \text{A GeV}$), which is covered by the HADES experiment [15-21] at the GSI facility. The HADES results confirmed previous measurements from the DLS collaboration [22]. In the future, the CBM experiment at FAIR [23] will add to the existing experimental data with new results from the intermediate energy range, specifically probing, together with complementary programs from NICA and J-PARC, the dilepton emission from the high net baryon density region.

To connect the theoretical calculations of the vector meson spectral functions with experimental measurements, dynamical approaches that describe the full evolution of heavy-ion collisions in detail have to be employed. Hadronic transport approaches are applied successfully [24-27] for low beam energy collisions. In the current work, a new hadronic transport approach, SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) [28], is introduced where the dilepton invariant mass contributions below the hadronic
thresholds are taken into account for all vector meson decay modes. Dilepton emission within hadronic transport approaches has been extensively explored by previous work using the GiBUU \cite{29}, the HSD \cite{30} and the UrQMD \cite{31} approach. These studies cover a variety of aspects concerning the dilepton production at low energies such as the effect of the coupling of the $\rho$ meson to baryonic resonances, Bremsstrahlung, the $\Delta$ contribution and the density dependence. They establish a solid foundation for the effort presented here. The motivation for revisiting the HADES dielectron results is manyfold. The calculation of the dilepton yield and subsequent comparison to experimental data allows to validate and constrain the resonance description and the new approach in general, while also enabling rich comparisons to other models. A well controlled baseline of the dilepton production for the hadronic sector with vacuum properties is also essential to study different resonance properties and the dilepton production at higher energies in the future e.g. in a hybrid approach, where the final state non-equilibrium emission is described within the same hadronic transport approach \cite{32,33}.

This work is outlined as follows: First, in Sec. II the SMASH approach is introduced with an emphasis on the employed resonance and dilepton production. The results in Sec. III are sorted by system size, where the studied systems are chosen according to the HADES program. As a start, the dilepton production in elementary reactions in Sec. IIIA and the cold nuclear matter scenario of proton-nucleus reaction in Sec. IIIB is calculated in order to establish the above mentioned baseline for the lepton pair emission. Afterwards, nucleus-nucleus collisions are studied in Sec. IIIC. For the large systems the coarse graining approach based on the same hadronic evolution is explored (Sec. IID), which enables to probe the sensitivity to medium modifications of the vector meson spectral functions in larger systems. This additionally permits a direct comparison between the dilepton emission based on a vacuum and in-medium description of resonances. Finally, a summary and outlook of the presented work is supplied in Sec. IV.

II. MODEL DESCRIPTION

A. SMASH

The approach applied in this work is SMASH (Simulating Many Accelerated Strongly-interacting Hadrons), which is a new hadronic transport approach for the dynamical description of collisions at low and intermediate beam energies and dilute non-equilibrium stages of heavy-ion collisions. The goal is to provide a standard reference for hadronic systems with vacuum properties. SMASH is a microscopic approach based on the relativistic Boltzmann equation. The collision term is modeled by excitation and decay of resonances and is restricted to binary collisions. Two particles collide, if the geometric collision criterion ($d_{\text{trans}} < \sqrt{\sigma_{\text{tot}}/\pi}$) is fulfilled. Only binary collisions and two body decays are performed in order to conserve detailed balance. Generic multi-particle decays (e.g. $\omega \to 3\pi$) are incorporated by assuming intermediate resonance states ($\omega \to \rho\pi \to 3\pi$). The model includes all well known hadronic degrees of freedom listed in the PDG \cite{34} up to a mass of 2.35 GeV. The agreement with elementary cross section data up to 4 GeV as well as reasonable agreement for proton and pion spectra with experimental data for $E_{\text{kin}} = 1 - 2A$ GeV is shown in \cite{28}, which also includes a comprehensive description of the approach. The version used for this work is SMASH-1.1.

1. Resonance description

Since dileptons are sensitive to resonance properties, the treatment of resonances is of great importance. In general, the current work mainly concentrates on vacuum spectral functions to provide a baseline for additional medium modifications.

All resonance spectral functions are relativistic Breit-Wigner functions:

$$A(m) = \frac{2N}{\pi} \frac{m^2 \Gamma(m)}{(m^2 - M_0^2)^2 + \Gamma(m)^2}. \quad (1)$$

Here $M_0$ is the (on-shell) pole mass and $m$ the actual off-shell mass of the resonance. The normalisation factor $N$ is chosen such that

$$\int_0^\infty dm A(m) = 1. \quad (2)$$

The spectral functions vanish at the combined mass of the lightest decay products. It is important to note that the dilepton decay mode is correctly taken into account as the kinematical threshold. The spectral functions of resonances that directly decay into a lepton pair ($R \to l^+l^-$) have contributions below the lightest combined mass of hadronic decay products, which is referred to as the hadronic threshold. In Fig. I the spectral function of the three vector mesons with dielectron decay channel are depicted as an example. The spectral functions peak at the pole mass $M_0$ and, as expected from their widths, the $\rho$ peak is the broadest, followed by the $\omega$ and the sharp $\phi$. Noticeable is the kink for the $\rho$ spectral function at around 300 MeV. The decay with the lightest hadronic decay products for the $\rho$ is $\rho \to \pi^\pm \pi^\mp$, so the hadronic threshold is at $2m_\pi$. This threshold leads to the kink, because the partial hadronic decay width of the $\pi$ decay vanishes at this mass. Since the $\rho$ can also decay into an $e^+e^-$ pair the spectral function continues down to $2m_e$. This is also true for the $\omega$ and the $\phi$. Both spectral functions also have contributions down to the combined...
mass of the actual lightest decay products - the dielectron mass.

This treatment of thresholds was introduced in [29] for the $\rho$ meson and marks a difference to other approaches [31, 35], which neglect the contributions below the hadronic threshold for numerical reasons. We find that they affect the dilepton spectrum in the low mass region (see section III A 1 and section III C 1). In a Monte-Carlo approach it is however challenging to numerically populate the mass region below the hadronic threshold, since the spectral function (Fig. 1) in this region only has small values. This leads to visible statistical fluctuations in some of the following dielectron invariant mass spectra.

The non-trivial shape of the spectral function, as e.g. seen in Fig. 1, originates from the mass dependent decay width $\Gamma(m)$, which is the sum of all partial decay widths for the different decay modes.

$$\Gamma(m) = \sum_i \Gamma_i(m) \quad (3)$$

The lifetime of the resonances is given as $\tau = 1/\Gamma(m)$. We have verified that changing the lifetime to be $\tau = 1/\Gamma(M_0)$ does not alter the results significantly. All hadronic partial widths are calculated following the framework of Manley et al. [36] (without taking the exact same parameters for the resonance properties). The partial width of a two-body resonance decay $R \rightarrow ab$ is calculated as follows

$$\Gamma_{R \rightarrow ab} = \Gamma_{R \rightarrow ab}^0 \frac{\rho_{ab}(m)}{\rho_{ab}(M_0)}. \quad (4)$$

The function $\rho_{ab}(m)$ is defined as

$$\rho_{ab}(m) = \int dm_a dm_b A_a(a_a) A_b(b_b) \times \frac{|\vec{p}_f|^2}{m} B_L^2(|\vec{p}_f| R) F_{ab}(m), \quad (5)$$

where $m_a$ and $m_b$ are the masses of the decay products $a$ and $b$, $A_{a/b}$ their respective spectral function and $|\vec{p}_f|$ the absolute value of the final-state momentum of $a$ and $b$ in the center-of-momentum frame. Equation 5 also includes the ”Blatt-Weisskopf functions” $B_L$ [37] and the form factor $F_{ab}$. For a more detailed description of the resonance treatment the reader is referred to [28]. The decay widths used for dielectron decays are described in section II B 1.

2. Elementary cross sections

Cross section data are in general a valuable tool to constrain the particle production for different collision energies. This section includes several results for particles that decay into dileptons. Their production therefore directly influences the dilepton production studied in this work. The cross section results complement the already reported total and single pion production cross sections in [28]. Beginning with the $\eta$ production cross section in $pp$ collisions, Fig. 2 shows the exclusive $\eta$ production in $pp \rightarrow pp\eta$. A good agreement is observed close to the threshold, whereas too many $\eta$ mesons are produced from $pp \rightarrow pp\eta$ for $\sqrt{s} > 3.25$ GeV. The disagreement however does not affect the few-GeV energy range of HADES measurements studied in this work. Error bars in Fig. 3 which shows the exclusive $\omega$ production cross section are large and SMASH results are in reasonable agreement with them. In the case of the $\rho$ meson, both inclusive ($pp \rightarrow p + X$) and exclusive cross sections ($pp \rightarrow pp\rho$) are shown (Fig. 4). Both are overestimated (solid lines) compared to the experimental data points, especially the exclusive cross section, which dominates the inclusive cross section for energies close to the threshold. It is important to consider here that the $\rho$ meson in SMASH is used as an intermediate state to emulate different Dalitz decays in two steps following the idea of strict Vector Meson Dominance [42]. The advantage of this treatment is the conservation of detailed balance. The two most prominent decays are the $3\pi$ decay of the $\omega$ ($\omega \rightarrow \rho \pi \rightarrow 3\pi$) and the $N^*(1520)$ dilepton Dalitz decay, which is emulated by $N^*(1520) \rightarrow \rho N \rightarrow e^+ e^- N$. Neglecting these additional proxy contributions (transparent lines in Fig. 4) leads to an agreement within errors for the inclusive cross section data point, but not for the exclusive channel. The overestimation in the inclusive $\rho$ production therefore can be seen as a compromise of the two-step treatment of three-body decays.

3. Isospin-asymmetric $\eta$ production

In general SMASH assumes isospin symmetry in the production of particles, but there are a few exceptions of this treatment for NN reactions. One is newly introduced for this work to improve the description of the dilepton yield stemming from the Dalitz decay of the $\eta$.
There exists experimental evidence that the η meson production via pn → pmη is enhanced in comparison to pp → pppη by approximately a factor of 6.5 \cite{43}. The dominant source of the η meson for low energies is the decay of N^*(1535), therefore we enhance its production following the suggestion from \cite{43} by modifying the matrix element.

\[ |\mathcal{M}_{pn \to NN^*(1535)}| = 6.5 \times |\mathcal{M}_{pp \to NN^*(1535)}| \]  

This introduction of isospin asymmetry in the production of N^*(1535) and consequently of η mesons greatly improves agreement with experimental data from \cite{43} as seen in Fig. 5.

### B. Dilepton production

Dileptons in SMASH are solely produced by direct or Dalitz decays of resonances (Table II).

| Resonance | Decays |
|-----------|--------|
| \( \rho \) | \( e^+ e^- \) |
| \( \omega \) | \( e^+ e^- \) |
| \( \phi \) | \( e^+ e^- \) |
| \( \pi \) | \( e^+ e^- \gamma \) |
| \( \eta \) | \( e^+ e^- \gamma \) |
| \( \eta' \) | \( e^+ e^- \gamma \) |
| \( \omega \) | \( e^+ e^- \pi^0 \) |
| \( \phi \) | \( e^+ e^- \pi^0 \) |
| \( \Delta^+ \) | \( e^+ e^- p \) |
| \( \Delta^0 \) | \( e^+ e^- n^0 \) |

The vector mesons \( \rho, \omega \) and \( \phi \) decay directly into a lepton pair, therefore the invariant mass of the pair equals the (off-shell) mass of the resonance. Although in principle direct decays of either electrons and muons are implemented, this work will focus on dielectrons only. Results of the dimuon production can be found in \cite{45}. Dalitz decays are incorporated for pseudoscalar mesons (\( \pi, \eta, \eta' \)), vector mesons (\( \omega, \phi \)) and \( \Delta \) baryons. All resonances are either produced by inelastic scattering, 2 → 1 absorption or decays of other resonances. This also means that directly decaying resonances, like e.g. the \( \rho \) meson, include Dalitz-like contribution by coupling to baryonic...
resonances via processes like $N^*/\Delta^* \to \rho X \to e^+e^-X$ (see section III A 1). Note that in addition to the modifications of the vector meson spectral functions due to the described explicit coupling to baryonic degrees of freedom, collisional broadening is dynamically taken into account by construction. In a dense hadronic medium, the chance for the resonances with electromagnetic decay channels to scatter with another particle before they decay is enhanced compared to reactions in the vacuum. This leads to a reduction of the lifetime and therefore an effective broadening. All dilepton decays are treated isotropically. Other transport models [29, 30] describing dilepton production for low energies additionally include non-resonant production of dileptons via NN and $\pi N$ Bremsstrahlung. Such contributions are neglected in this work, but remain a possible extension of this approach in the future.

1. Decay widths and form factors for dilepton decays

The decay width for direct decays $\Gamma_{V \to l^+l^-}(m_{ll})$ with $V = \rho, \omega, \phi$ under the assumptions of Vector Meson Domi- nance [40] is

$$\Gamma_{V \to l^+l^-}(m_{ll}) = \frac{\Gamma_{V \to l^+l^-}(M_0)}{M_0} \frac{M_0^3}{m_{ll}^3} \times \sqrt{1 - \frac{4 m_{ll}^2}{m_{ll}^2} \left(1 + \frac{2 m_{ll}^2}{m_{ll}^2}\right)} \left(1 + \frac{m_{ll}^2}{m_{ll}^2}\right)^2$$

with $m_{ll}$ being the invariant mass of the lepton pair, $M_0$ the pole mass of the vector meson and $m_l$ the lepton mass. For $\Gamma_{V \to l^+l^-}(M_0)$ values from the PDG [34] are used. The $m_{ll}$ dependence can also be observed in Fig. 1 for contributions to the spectral function below the hadronic threshold (red dashed line), where only the dilepton width is contributing.

For Dalitz decays the invariant mass of the dilepton is not fixed by the mass of the decaying resonance, because of the three decay products. Hence only a differential decay width $d\Gamma/dm_{ll}$ is given. For the pseudoscalar Dalitz decays $P = \pi^0, \eta, \eta'$ the differential width is given by [47],

$$\frac{d\Gamma_{P \to e^+e^-}}{dm_{ll}} = \frac{4\alpha}{3\pi} \frac{\Gamma_{P \to \gamma\gamma}}{m_{ll}} \left(1 - \frac{m_p^2}{m_{ll}^2}\right)^3 |F_P(m_{ll})|^2$$

with $\Gamma_{\pi^0 \to \gamma\gamma} = 7.6 \cdot 10^{-6}$ MeV, $\Gamma_{\eta \to \gamma\gamma} = 5.2 \cdot 10^{-4}$ MeV and $\Gamma_{\eta' \to \gamma\gamma} = 4.4 \cdot 10^{-3}$ MeV [34], $\alpha = 1/137$ and $m_p$ the mass of the pseudoscalar meson. The form factors $F_P$ are

$$F_{\pi^0}(m_{ll}) = 1 + b_{\pi^0} m_{ll}^2, \quad b_{\pi^0} = 5.5 \text{ GeV}^{-2},$$

$$F_{\eta}(m_{ll}) = \left(1 - \frac{m_{ll}^2}{\Lambda_{\eta}^2}\right)^{-1}, \quad \Lambda_{\eta} = 0.716 \text{ GeV}$$

with $\Lambda_{\eta}$ taken from [48]. For the $\eta'$ form factor the QED approximation $F_{\eta'}(m_{ll}) = 1$ is used. The vector-meson Dalitz decays ($V = \omega, \phi$) are parametrised by [17, 49],

$$\frac{d\Gamma_{V \to \pi^0e^+e^-}}{dm_{ll}} = \frac{2\alpha}{3\pi} \frac{\Gamma_{V \to \pi^0\gamma}}{m_{ll}} \times \left[1 + \frac{m^2_{V}}{m_{ll}^2 - m^2_\eta}\right]^{-1} \left(1 + \frac{4 m^2_{V} m^2_{\pi}}{(m^2_{V} - m^2_\eta)^2}\right)^{3/2} \times |F_V(m_{ll})|^2, \quad (11)$$

where $m_V$ is the mass of the vector meson, $m_\eta$ the pion mass and

$$|F_V(m_{ll})|^2 = \frac{\Lambda^4_{\eta}}{(\Lambda^2_{\eta} - m^2_\eta)^2 + \Lambda^2_{\omega} m^2_{ll}}.$$  

The other parameters are set as follows: $\Gamma_{\omega \to \pi^0\gamma} = 0.703$ MeV, $\Gamma_{\phi \to \pi^0\gamma} = 5.4$ MeV [34], $\Lambda_{\omega} = 0.65$ GeV and $\Gamma_{\omega} = 75$ MeV [49]. For the $\phi$ form factor the QED approximation $|F_{\phi}(m_{ll})|^2 = 1$ is chosen. Note, that in previous work [80] the possibility of describing these decays, similar as the hadronic $V \to 3\pi$ decays, in two steps via an intermediate $\rho$ meson $V \to \rho X \to \pi^0 e^+e^-$ has been explored. This would render the parameterizations given above obsolete and remains an appealing option for the future. For this work we have chosen to use the more established direct treatment, which also allows more direct comparison to similar approaches [29, 31] that rely on the same formalism.

For the $\Delta$ Dalitz decay, the differential decay width by Krivoruchenko et al. [51] is applied,

$$\frac{d\Gamma_{\Delta \to N e^+e^-}}{dm_{ll}} = \frac{2\alpha}{3\pi} \frac{\Gamma_{\Delta \to N\gamma\gamma}}{m_{ll}}, \quad (13)$$

$$\Gamma_{\Delta \to N\gamma\gamma}(m_{ll}) = \frac{\alpha}{16} \frac{(m_\Delta + m_N)^2}{m^3_\Delta m^2_N} \times [(m_\Delta + m_N)^2 - m_{ll}^2]^{1/2} \times [(m_\Delta - m_N)^2 - m_{ll}^2]^{3/2} \times |F_\Delta(m_{ll})|^2. \quad (14)$$

The form factor $|F_\Delta(m_{ll})|^2$ is a topic of ongoing debate [52] and not well constrained by experimental data. Therefore, it is chosen to be constant and fixed at the photon point $F_\Delta(0) = 3.12 \equiv F_\Delta(m_{ll})$, where it is known that $\Gamma_{\Delta \to N\gamma}(0) = 702$ MeV [34].

2. Shining method

In experiment as well as in theory a major challenge of electromagnetic probes is their rare production. For dileptons the decay branching ratios are small, typically
on the order of $10^{-5}$. Leptons are therefore treated perturbatively by the so called Time Integration Method, also referred to as Shining Method \cite{53,54}. The idea is to obtain the dilepton yield $\Delta N_{l^-}^{-}$ by integrating the decay probability of the dilepton decay mode $\Gamma_{l^-}^{-}$ over the Lorentz-corrected ($\gamma$) lifetime $\tau = t^f - t^* \leq 0$ of a given resonance:

$$\Delta N_{l^-}^{-} = \int_{t^*}^{t^f} \frac{dt}{\gamma} \Gamma_{l^-}^{-}.$$

(15)

This is done numerically by continuously emitting (shining) dileptons during the propagation of a resonance and weighting them by taking their decay probability into account. Such a perturbative treatment neglects any secondary interactions of the leptons after the decay, e.g. by the Coulomb force. This is justified since leptons only interact via the weak electromagnetic interaction and are not perturbed by strong interactions.

### III. RESULTS

This section is separated into four main parts covering all available experimental data for dilepton production in low beam energy collisions. First, elementary reactions are studied to confirm the hadronic baseline in our transport approach. Afterwards results for nuclear systems, sorted by system size starting with p+A and ending with Au+Au collisions, are presented. The last part is focused on the coarse-grained hadronic space-time evolution in Au+Au collisions, are presented. The last part is focused on the coarse-grained hadronic space-time evolution including medium-modified spectral functions. In general, contributions from all decay channels (Table I) are taken into account, but for the Dalitz decays of $\phi$ and $\eta'$ in particular only negligible contributions are observed for the systems studied here. Therefore, almost all results exclude both channels. All results that include experimental data from HADES are filtered using the HADES acceptance filter (HAFT \cite{53}). Additionally, in order to match the experimental analysis procedure an opening angle ($\Theta > 9^\circ$) cut and the single lepton momentum cut for the specific system have been applied.

#### A. Elementary collisions

Elementary collisions offer the possibility to constrain and test the description of the binary reactions occurring in a nucleus-nucleus collision. Therefore, they represent a baseline for the dilepton production in collider experiments. Results for three different systems are shown: proton-proton, neutron-proton and $\pi$-proton. For the sake of data comparison the same energies as measured by HADES were chosen \cite{15,16}. Results for the pion beam are not published yet, so predictions, which are not filtered for acceptance, are shown.

![Fig. 6. Invariant mass spectrum of dielectrons produced by pp collisions at $E_{\text{Kin}} = 1.25$ GeV. Experimental data from \cite{15}.](image)

![Fig. 7. Invariant mass spectrum of dielectrons produced by pp collisions at $E_{\text{Kin}} = 2.2$ GeV. Experimental data from \cite{16}.](image)

1. **pp**

Dilepton production for proton-proton (pp) reactions is calculated for three different kinetic energies $E_{\text{Kin}} = 1.25/2.2/3.5$ GeV in a fixed-target setup. Fig. 6 and Fig. 7 show the dilepton invariant-mass spectrum for the two lower energies in comparison to HADES data \cite{15,16}.

For the reaction at $E_{\text{Kin}} = 1.25$ GeV (Fig. 6) only four different channels of the whole dilepton cocktail are contributing. The $\pi^0$ Dalitz decay dominates in the low invariant-mass region up to around 150 MeV. Above 150 MeV in the intermediate mass region, the Dalitz decay of the $\Delta^+$ decay is dominant. Since the $\Delta^+$ and the $\Delta^0$ contributions are plotted separately a difference of more than one order of magnitude can be observed. The $\Delta^+$ is more likely to be produced, since it can be a product of the primary collision, whereas the $\Delta^0$ can only be formed in secondary reactions due to charge conservation and the fact that only $2 \rightarrow 2$ reactions are allowed in SMASH.

In the higher invariant-mass region a large contribution from the direct $\rho$ meson channels is noticed. The total yield is in good agreement with experimental data.
FIG. 8. Invariant mass spectrum of dielectrons produced by pp collisions at $E_{\text{Kin}} = 3.5\text{ GeV}$. Experimental data from [17].

Since a kinetic energy of $E_{\text{Kin}} = 1.25\text{ GeV}$ is slightly below and $E_{\text{Kin}} = 2.2\text{ GeV}$ is above the $\eta$ production threshold, a contribution from the $\eta$ meson is seen in Fig. [7]. Also, additional significant contributions from $\omega$ decays are observed for the higher kinetic energy. Here, the $\eta$ yield is dominant for the low and lower intermediate invariant mass region up to around 400 MeV. The $\pi$ again dominates for low invariant masses and the $\rho$ in the higher intermediate mass region above 400 MeV. The peak in the $\omega \rightarrow e^+ e^-$ spectrum at the $\omega$ pole mass can already be observed for this kinetic energy. The overall agreement with data is again reasonable.

Fig. 8 shows the invariant mass spectrum produced by fixed target pp reactions with a kinetic energy of 3.5 GeV. Because of the higher energy the spectrum reveals two new features: a more pronounced $\omega$ peak and an additional $\phi$ contribution. The significant contributions to the spectrum now reach up to 1.1 GeV. Again, a good agreement with experimental data is observed. In Appendix A, $p_T$ and $y$ spectra for different invariant mass windows are shown for completeness.

The contributions from the direct decays of the vector mesons with masses reaching below the hadronic thresholds are important for all three energies. They originate from the resonance description introduced in Sec. [1A1] that considers the dilepton decays for the spectral function. In case of the $\rho$ meson, those contributions are significant in the intermediate mass region. For the $\omega$ they are negligible compared to e.g. the $\omega$ Dalitz decay. Nevertheless, Fig. 8 shows that contributions below the hadronic threshold are consistently observed for both - $\omega$ and $\rho$ meson. This also holds true for all vector mesons including the direct $\phi$ decay, but low invariant-mass contributions in pp are too small to be visible for the $\phi$ meson on the chosen scale.

After discussing the general features of dilepton production in pp collisions, the focus in the following will be on the contribution from the vector mesons.

The previously shown findings for the elementary cross-section of $\rho$ mesons measured in the hadronic channel (Fig. 4) translate directly to the corresponding dilepton spectra. At low energies ($E_{\text{Kin}} = 1.25$ and 2.2 GeV), where the overestimated exclusive $\rho$ production via $pp \rightarrow ppp$ is dominant, the $\rho$ yield is large, meaning it pushes the total yield to the upper limits of the error bars, whereas for the highest kinetic energy ($E_{\text{Kin}} = 3.5\text{ GeV}$) this is not the case. Overall, the overestimation of the exclusive cross-section does not result in an overestimation of the total dilepton yield, which indicates that the inclusive $\rho$ production is in line with the experimental dilepton results.

In order to fully understand the dilepton production the origin of the $\rho$ and $\omega$ resonance is investigated. Earlier studies [11, 24, 56, 57] revealed that in particular the coupling of the vector mesons to baryonic resonances is of importance. Such information is however challenging to obtain in experiment alone. Comparisons to theoretical models that keep track of the whole process history give...
insight into important couplings by splitting the $\rho$ and $\omega$ contributions by origin. Additionally, such studies offer the possibility to constrain resonance properties such as branching ratios.

At the top of Fig. 9 the different contribution to the overall $\rho$ dilepton yield (thick blue line, same as in Fig. 8) are shown for pp reactions at a kinetic energy of 3.5 GeV. To allow comparisons to the overall invariant mass spectra, all dileptons in Fig. 9 are also acceptance filtered. Two different processes are important: $\pi^+\pi^-$ annihilation and the decays of different baryonic resonances. The annihilation process has a small yield as expected in elementary pp collisions, because it requires rare secondary scatterings. While the $\pi\pi$ process of course has a threshold at $2m_\pi$, the significant contributions below this threshold come from Dalitz-like contribution of the lighter baryonic resonances ($B^* \to \rho N \to e^+e^-N$, $B = N, \Delta$), mainly $N^*(1520), \Delta^*(1620)$ and $\Delta^*(1700)$. These populate the large low mass tail of the overall $\rho$ yield. The different shape of the $N^*(1520)$ is due to the kinematic limitation that the on-shell mass of the resonance is too small to produce a $\rho$ at the pole mass in the reaction $N^* \to N\rho$. For higher invariant masses, higher baryonic resonances are important. Especially, the combined heavy $N$ states ($N^*(2080), N^*(2190), N^*(2220), N^*(2250)$) dominate the high mass tail. Other contributions include higher mesonic states and baryonic resonances that have no significant effect on the overall $\rho$ contribution.

Fig. 9 also shows the differences to the overall $\omega$ yield (thick green line, same as in Fig. 8) at the bottom. Since the $\omega$ width is much smaller, it shows a very clear peak structure at its pole mass in the invariant mass spectrum; $\omega$s are mainly produced by nucleon resonance decays in significant portions. A clear mass ordering can be observed. The lightest baryonic resonances, $N^*(1710), N^*(1875)$, have the largest contributions followed by the heavier resonances in order of their pole masses. The contribution below the hadronic thresholds that mainly forms the low mass tail is the $N^*(1710)$ resonance, which is also the lightest resonance that can decay into $\omega$ with a pole mass below the $m_N + m_\omega$ threshold.

Overall the dilepton production in SMASH for pp collisions as the cleanest probe for elementary collisions is well understood and in good agreement with experimental data and offers a solid base to study larger systems.

2. np

The next system of interest is the elementary neutron-proton (np) system. Dilepton production has been measured by HADES, realizing np collisions by using a deuterium beam on a proton target and triggering on forward-going protons. These reactions are called quasi-free. Since the deuteron is a bound system the nucleons inside carry additional momentum. The results for this work were obtained following an ansatz referenced in the HADES publication [15]. The neutron projectile is given additional momentum according to the momentum distribution of the PARIS potential [58, 59], neglecting the relatively small binding energy of the deuteron itself.

Fig. 10 shows results for the dilepton production of quasi-free np reactions at $E_{Kin} = 1.25$ GeV. The additional momentum of the neutron inside the deuteron leads to a higher kinematic threshold than in the pp case (Fig. 9) for the same energy, so contributions up to 600 MeV are significant. The same channels as in pp are contributing, but, because the energy now reaches above the $\eta$ threshold, an additional $\eta$ yield is observable. In addition, the isospin asymmetry between $\Delta^+$ and $\Delta^0$ does not exist anymore, since both are equally likely to be excited in a primary collision. The low-mass region is dominated by the $\pi$ contribution. In the intermediate-mass region $\eta, \Delta$ and $\rho$ are all contributing, while for masses above 400 MeV the direct $\rho$ decay becomes the dominant contribution.

Compared to the HADES data [15] a sizeable underestimation is observed for masses higher than 150 MeV suggesting that the $\pi$ contribution is described reasonably well, but other channels are underestimated. Judging by the shape an enhancement in the $\eta$ as well as in the $\rho$ contribution would improve the agreement with experimental data. The $\Delta$ on the other hand falls too steeply to match the shape of the experimental data. Possible extensions that would enhance the total yield include the addition of np Bremsstrahlung, or a np $\to \eta\gamma$ channel. Such extensions were, however, not successful in describing the experimental data in the similar GiBUU transport model [29]. Similar to other transport approaches [29, 30] the np system seems to be only underestimated at this specific low energy. The later discussed carbon-collisions for example, which are close to a superposition of pp and np collisions, only show a similar systematic underestimation of the dilepton production around the same energy of 1.4 GeV. For higher energies the agreement with experimental measurements improves.
FIG. 11. Invariant mass spectrum of dielectrons produced by \( \pi p \) reactions at \( E_{\text{Kin}} = 0.56 \text{ GeV} \).

considerably. Because \( np \) reactions also only constitute a fraction of the binary scatterings in a nucleus-nucleus collision, improvements are left for future work. For the description of possible extensions the reader is referred to [29]. How to correctly describe the \( np \) dilepton spectrum within a hadronic transport framework remains an interesting open question.

3. Pion beam

Besides the discussed NN reactions, pion-beam reactions, where \( \pi^- \) scatter on a proton target, are considered. The kinetic energy of \( E_{\text{Kin}} = 0.56 \text{ GeV} \) matches upcoming HADES results [60] for this system and is specifically chosen to probe the \( \rho \) production around the \( N^*(1520) \) pole mass.

Indeed, the \( \rho \) dilepton decay is observed to be the dominant contribution to the dilepton invariant mass spectrum from \( \pi p \) at \( E_{\text{Kin}} = 0.56 \text{ GeV} \) (Fig. 11). Only for invariant masses lower than 150 MeV it is exceeded by the \( \pi \) decay contribution. Other smaller contributions include \( \eta \) and \( \Delta^0 \), negligible are \( \Delta^+ \), \( \omega \) and \( \phi \). Compared to pp the ordering of the \( \Delta^+ \) and \( \Delta^0 \) is inverted for this system due to the same reason as mentioned before: because of charge conservation only \( \Delta^0 \) can be produced in primary collisions. The sharp kinematic threshold at 0.56 GeV due to the available center of mass energy is noticeable as well. The red dashed line in Fig. 11 indicates the \( N^*(1520) \) contribution to the \( \rho \) spectrum. It is the only relevant contribution to the \( \rho \) spectrum and with this to the overall spectrum above 150 MeV. Therefore this setup provides a good opportunity to test and constrain the coupling of the \( \rho \) to the \( N^*(1520) \). Currently SMASH treats the \( N^*(1520) \) Dalitz decay \( (N^*(1520) \rightarrow e^+e^-N) \) via the strict Vector Meson Dominance assumption, where the resonance decays via an intermediate \( \rho \) meson. Once experimental data is available it will be possible to test that assumption and compare it with a simple “QED point-like” \( R_{\gamma^*} \)

FIG. 12. Invariant mass spectrum of dielectrons produced by \( pNb \) reactions at \( E_{\text{Kin}} = 3.5 \text{ GeV} \). Experimental data from [18].

model [61], where the Dalitz decay is performed directly and the involved electromagnetic form factor is chosen to be constant.

B. Proton-nucleus collisions

The dilepton production in proton-nucleus (pA) collisions, as a cold nuclear matter scenario, is discussed for a proton projectile that scatters on a Niobium target with \( E_{\text{Kin}} = 3.5 \text{ GeV} \) (pNb).

A comparison to HADES data [18] of the invariant electron-pair mass spectrum is displayed in Fig. 12. In the low-mass region, the \( \pi \) and \( \eta \) contributions are prominent. The \( \pi \) peak is slightly overestimated. This hints at a problem with the normalization, which may be caused by the model-dependent pNb cross section \( \sigma_{pNb} = 848 \text{ mb} \) used in [18]. The experimental data also reveal a stronger shoulder around 500 MeV.

Besides the dominant \( \rho \) and \( \omega \) contributions in the mass region from 500 MeV up to 900 MeV, a strong \( \phi \) peak surfaces around 1 GeV. The \( \phi \) production is experimentally not well known. Neither \( N^* \rightarrow \phi N \) branching ratios nor the \( pp \rightarrow pp\phi \) cross section beyond the threshold are constrained by experimental data. Therefore, the simple ansatz reported in [62] is followed in this work. All nucleon resonances with a pole mass of 2080 MeV or higher decay into \( N\phi \) with a fixed branching ratio. The \( \phi \) peak in pNb allows to constrain the fixed branching ratio within our approach to a value of 0.5%, which is larger than the value reported in [62]. Note, because of the larger system also medium effects like absorption play a role. Unfortunately, the corresponding elementary pp data that would offer a clean vacuum reference only provides an upper bound in the \( \phi \) peak mass region due to large error bars. Nevertheless, the obtained value is consistent with this bound, since an agreement within error bars is seen in Fig. 8.
Overall experimental data and SMASH results are in good agreement. This indicates that the dilepton production cross section in np collisions at this energy is in better agreement with experimental results than for the lower energy of 1.25 GeV discussed in Sec. III A 1 since initial pp and np reactions are roughly equally contributing to the overall pA yield. The pA yield also seems not to be particular sensitive to medium modifications of resonance properties, since the approach used for the present work relies entirely on the resonance description with vacuum properties, neglecting explicit medium modifications, while still describing the yield well. Only the underestimation around 500 MeV might hint at an onset of an additional broadening of the ρ-like contribution.

In App. B two additional invariant mass spectra can be found for two different dilepton momentum windows (0 < p_ee < 800 MeV and p_ee > 800 MeV) for completeness.

C. Nucleus-nucleus collisions

The main goal of research in this field is to study heavy-ion collisions. In the following, results for three different nucleus-nucleus collision systems are shown and compared to experimental data, wherever available. This section also addresses the question, which spectra are sensitive to possible in-medium modifications by deviating from results based on vacuum properties. It builds on the validation presented above that the dilepton production in elementary and cold nuclear matter is well described by the SMASH transport approach.

1. CC

Light nucleus-nucleus collisions offer a good starting point for studying dilepton production under the assumption of vacuum resonance properties in larger collision systems. Results in this section include invariant mass spectra of the produced dielectrons in carbon-carbon (CC) collisions for two kinetic energies: E_{Kin} = 1.0 A GeV and E_{Kin} = 2.0 A GeV.

Fig. 13 shows the spectrum for the lower beam energy. The main contributions originate from the π, Δ, η and ρ channels. The ω decays do not have a large impact on the overall yield. The Δ^0 and Δ^+ yields are lying on top of each other, due to the equal numbers of protons and neutrons, and therefore similar production probability. The comparison with HADES data [19] reveals a disagreement in the intermediate mass region between 150 and 400 MeV. Even though the shape potentially matches the data, the total yield is underestimated. This can be understood recalling the previously discussed elementary results in Sec. III A 1 and Sec. III A 2. The dilepton production in pp collisions is in good agreement with data, but too few dielectrons are produced by np collisions, in consequence an underestimation around the same kinetic energy is expected, since CC is known to be close to a mere superposition of binary NN reactions [15].

The results for the dilepton invariant mass spectrum in CC collisions at the higher energy of E_{Kin} = 2.0 A GeV are shown in Fig. 14. The π and η contributions dominate the spectrum up to 400 MeV, while above this mass the yield mainly consists of ρ and ω contributions. At the highest masses, the φ peak is broadened due to the low resolution of the detector. The data [20] are nicely described by the total yield. In the region around the ω-pole mass (M_{0,ω} = 783 GeV), the ρ and ω contributions are slightly overestimated. Compared to the most recent results from the similar UrQMD transport approach for the same system [63], the results presented here are in better agreement with the data, in particular in the intermediate mass region. The different thresholds of the vector meson contributions of the ρ and the ω lead to notable differences. The ρ is, as the second largest contribution, a significant contribution in the intermediate-mass region. The ω low-mass tail is not important for the overall yield, but the consistent treatment of both vector mesons is visible. The consistent treatment includes the
The $\phi$ meson, but its yield is again too small to be visible on the chosen scale.

The fact that the description of the dilepton production with SMASH matches the data for $E_{\text{Kin}} = 2.0\,\text{A GeV}$ further validates the resonance treatment and the approach in general. It also shows that no explicit medium modifications seem to be necessary to describe the dilepton production for such small systems or at least that invariant-mass dilepton data are not sensitive to such modifications. It is important to mention, however, that transport approaches include a different medium effect intrinsically - *collisional broadening*. If the density rises locally, the probability of collisions also rises and therefore the lifetime of resonances decreases effectively. By the relation $\tau = 1/\Gamma(m)$ this can be translated into a broadening, even if the description of the resonances is still based on vacuum properties.

2. ArKCl

On the basis of the above shown solid description of elementary and small nucleus-nucleus systems, larger systems are explored. A good example for a larger, intermediate-sized collision system is the ArKCl system at $E_{\text{Kin}} = 1.76\,\text{A GeV}$ measured by HADES [21]. Within SMASH it is modeled with a $^{40}\text{Ar}$ projectile hitting a $^{37}\text{Ar}$ nucleus target to emulate an average of the $^{35}\text{Cl}$ and $^{39}\text{K}$ composition.

Like most of the discussed dielectron invariant mass spectra, the ArKCl yield is dominated by $\pi$ and $\eta$ in the low and the vector mesons ($\rho$, $\omega$, $\phi$) in the higher invariant mass region above 500 MeV. Since there are more neutrons than protons in the colliding nuclei, the $\Delta^0$ is slightly above the $\Delta^+$ yield. Although the spectrum is in reasonable agreement with the experimental data [21] for low and highest invariant masses, two distinct issues are revealed by the comparison to experimental data. First, the $\rho$ contribution is too large in the region between 600 and 800 MeV. This might be connected to the overproduction in the exclusive $\rho$ cross section discussed in Sec. [IIA.2]. The $\rho$ in $p+p$ reactions at $E_{\text{Kin}} = 1.76\,\text{A GeV}$ ($\sqrt{s_{NN}} = 2.61\,\text{GeV}$) is almost solely produced by the overestimated exclusive process $pp \rightarrow ppp$ (Fig. [3]). The second issue is an underestimation in the mass region between 150 MeV and 500 MeV.

In combination both issues indicate the limit of the assumption of resonances with vacuum properties. The intermediate mass region is known to be enhanced by medium modifications, i.e. a broadening of the vector meson spectral functions, in particular of the $\rho$ meson [2]. This broadening has also an influence on the $\rho$ pole mass region, since the yield in this region will be decreased by a broadening.

This result therefore suggests that dilepton emission in systems as large as ArKCl is sensitive to medium modifications of resonances that go beyond the intrinsic collisional broadening mentioned above. To verify this hypothesis, a comparison with a coarse-graining approach [65] that employs explicit medium modifications of the spectral functions is presented in Sec. [III.D].

3. AuAu

The largest collision system discussed in this work is gold-gold (AuAu) scattering at $E_{\text{Kin}} = 1.23\,\text{A GeV}$, matching upcoming HADES results [66].

The invariant mass dielectron spectrum (Fig. [16]), which is not acceptance filtered, reveals some differences to the previous cases even without a comparison to experimental data. The $\Delta$ yield is larger in relation to other contributions than for smaller systems. The $\phi$ peak is most prominent in this spectrum and the $\rho$ contribution shows a slight bump at the pole mass, since the reaction $\pi\pi \rightarrow \rho$ dominates over the different Dalitz-like $N^*$ and $\Delta^+$ contributions. Both effects can be explained by the large amount of secondary reactions. Fig. [16] also shows an $\eta'$ contribution, which is only visible since a large ver-
tical scale is chosen for this plot. This illustrates that its contribution is negligible, especially for smaller systems. Furthermore, the limited statistics also suggests that η′ are produced rarely even in a large system. Even though the statistics is limited below the hadronic threshold, it can be seen that the direct ω contribution might be on the same order of magnitude as the ω Dalitz contribution.

Extrapolating from the already performed experimental data comparisons, an even larger underestimation in the intermediate mass region, due to the greater importance of medium effects, and an overestimation in the ρ pole mass region is expected for a future experimental data comparison. New data will be valuable to further constrain e.g. the φ production, as well as clarifying the role of medium effects.

D. Coarse-Graining Approach

In order to investigate the effect of explicit medium modifications, the hadronic evolution of SMASH is coarse grained (CG) in this section. This means that macroscopic quantities are extracted locally from the microscopic transport model, enabling the determination of thermal dilepton emission from those regions. The dilepton radiation is therefore a mix of dilepton production from thermal dilepton emission rates and the usual hadronic transport contributions. The framework used for this work is the same as in [63] and has proven to be reliable in describing experimental data from SIS up to LHC energies [63, 67, 68]. In the following, a brief summary of the approach is given, for a comprehensive review the reader is referred to [65]. The approach locally averages over the reaction evolution by splitting an ensemble of collision events into small space-time cells. For those cells the baryon density ρ_B and the energy density ϵ are calculated in the rest-frame. Knowing both and assuming (for the beam energies considered in this work) a hadron resonance gas equation of state, the local temperature T and baryon chemical potential μ_B are determined. Based on the thermodynamic information, the yield of dileptons from a certain cell is given by the corresponding thermal emission rates, that include the medium effects on the vector meson spectral function. The in-medium description used in the coarse-grained approach employed here are based on hadronic many-body theory [10, 57], where the spectral function depends on temperature and density. Since medium effects at these energies are only expected to affect the ρ and ω significantly, dilepton yields from thermal rates are only calculated for these two. If the temperature drops inside the cells, the assumption of thermal rates is no longer reasonable; therefore also non-thermal (freeze-out) transport contributions are included, which are known to be of significance only around the pole masses [55]. The ω Dalitz decay is also part of the ω freeze-out contribution. Thermal rates together with the freeze-out contribution form the coarse-graining contributions for the ρ and ω (CG-ρ and CG-ω). The last contribution from the coarse-graining approach are multi-π states originating from broad resonances. The dilepton cocktail is completed with the relevant transport contributions of π, η and φ from SMASH.

Before looking at the results for dilepton emission in the context of the experimental data, let us show the thermodynamic properties of the system. An example for the evolution of the baryon ρ_B and energy ϵ density in units of the ground state density in ArKCl and AuAu collisions at SIS energies is given in Fig. 17 for the central cell at the origin of the coarse-graining grid. As expected, initially the density rises similarly for both studied systems, while for the AuAu collisions both densities rise higher and reach a larger maximum (5 × ground state density) later. For both systems the density falls with time, but faster for the smaller ArKCl system. For AuAu a density plateau is observed from 5 – 15 fm.

Fig. 18 shows the temperature T and baryochemical potential μ_b in the most central cell over time for ArKCl collisions at E_{kin} = 1.76A GeV and AuAu collisions at E_{kin} = 1.23A GeV.
The baryon chemical potential quickly rises to a value of around 900 MeV (Fig. 18 shows $\mu_B/3$) at 5 fm for both systems. The temperature reaches its maximum of 100 MeV around 8 fm and is similar for ArKCl and AuAu. In this case, the plateau in the chemical potential for AuAu even extends from 5 to around 22 fm. Note that the values shown here are maximum values at the point of highest density in the system to indicate the reach in the phase diagram.

In summary, the presented results confirm that the cell evolution is reasonable, since the expectation as well as results reported in [65] that are based on hadronic space-time evolution of UrQMD are matched. This not only further validates the SMASH approach, but forms the basis for the more advanced analysis of the dilepton emission of the coarse-grained evolution.

Results for two large systems are presented in the following: ArKCl and AuAu. The two different approaches used in this work are compared in the following: First, the dilepton yield from the transport model SMASH as discussed in the previous sections (referred to as non-CG); although the medium effect of collisional broadening is included, no explicit medium effects are incorporated. Second, the outcome from the coarse-graining approach, which employs thermal rates including explicit in-medium effects for the $\rho$ and $\omega$ meson; those medium-modified dilepton contributions are combined with unmodified cocktail contributions ($\pi$, $\eta$, $\phi$) from the SMASH simulations.

1. ArKCl

First, the focus is on the dilepton emission from ArKCl collisions at $E_{\text{kin}} = 1.76 A$ GeV. The total SMASH vacuum transport result (non-CG) is underpredicting the invariant mass spectrum for this system in the intermediate mass region and overpredicting it in the $\rho$ pole mass region (as discussed in Sec. III.C.2). Fig. 19 shows the results from the coarse-graining approach, which again are cut in momentum and angular distribution as well as filtered for the acceptance [55] in order to compare to experimental data from HADES [21]. All solid lines refer to SMASH dilepton production (same as in Fig. 15). Out of these only the $\pi$ and $\phi$ yields are important for the overall spectrum at low and high invariant masses respectively. The dashed contributions for $\rho$ and $\omega$ display results from the coarse-graining approach and include the thermal dilepton rates containing medium modifications and the freeze-out contributions for cold cells. Also, the multi-$\pi$ contribution is added, but has only little effect on the overall spectrum due to the low beam energy. On the contrary, the effects on the vector meson dilepton yield are large. For both, $\rho$ and $\omega$, the yield is shifted from the pole mass to the low-mass region.

This is even better visible in the direct comparison between the vector meson yields in Fig. 20 where an enhancement of the low mass tail together with a decrease in the pole mass region, especially for the $\rho$ yield can be observed, as expected from a broadening scenario of the vector meson spectral function. The $\rho$ yield from the coarse graining shows an almost exponential decrease with mass and dominates the spectrum over most of the covered invariant-mass range.

Quantitatively, the agreement of the overall yield (all) with experimental data [21] in Fig. 19 is greatly improved with the medium modifications of the vector meson spectral functions employed in the coarse-graining approach compared to the SMASH dilepton production based on vacuum resonance properties. Only the normalization on the $\pi$ multiplicity leads to an overestimation of the $\pi$ peak for low invariant masses and consequently also to a slight overprediction around 150 MeV. It can be concluded that a sensitivity to medium modifications in the ArKCl spectrum is confirmed within our approach.
For the larger AuAu system the effect of medium modifications is expected to be larger than in ArKCl collisions. Predictions for AuAu collisions at $E_{K\text{in}} = 1.23A\,\text{GeV}$ within the coarse-graining approach, which are not acceptance filtered, are shown in Fig. 21. Even though no experimental data constraints are available yet, the comparison of the SMASH dilepton result for the total yield from Fig. 16 (non-CG) with the spectrum from the coarse-graining approach (all) already hints at a larger modification of the yield. Differences are observed in the intermediate-mass region and around vector meson pole masses analogously to ArKCl, but the effect in the intermediate-mass region seems more pronounced. Also in the high invariant-mass region the multi-$\pi$ contribution leads to deviations. Again the only relevant yields from the SMASH contributions are the $\pi$ and $\phi$ channel.

Fig. 22 again shows the shift in the yield away from the pole masses for $\rho$ and $\omega$. For the $\omega$ the broadening of the peak and for the $\rho$ the important enhancement of the low-mass tail is nicely observed. Since no acceptance filtering affects the shape of the yields here, the Dalitz-like tail for low masses in the SMASH $\rho$ contribution stemming from the different baryonic-resonance contributions (compare Fig. 9) is clearly seen. Although this is not a medium effect, since it is already observed in proton-proton reactions, the underlying mechanism leading to the pronounced low mass tail, namely the coupling of the $\rho$ to baryonic resonances, is the same that is found to be important for the medium modifications of the spectral functions used in the coarse graining framework [10, 57].

The findings for both ArKCl and AuAu align nicely with previous results obtained with the UrQMD coarse-graining transport approach [65]. The presented study allows to add a direct comparison between a coarse-graining approach and the dilepton production from a hadronic transport approach, since both rely on the same hadronic evolution. In summary, the transport approach overall reveals similar features as an in-medium description in the dilepton spectra due the coupling to baryonic resonance together with collisional broadening. Nevertheless, the transport description falls short for larger systems beginning with ArKCl, but is able to account for dilepton emission in smaller systems up to CC.

IV. SUMMARY AND OUTLOOK

In this work the complete set of available dielectron production measurements at SIS energies based on a new hadronic transport approach (SMASH) is discussed. SMASH relies on resonance interactions with vacuum properties and the corresponding dilepton production is validated by a good agreement with experimental data in proton-nucleus and nucleus-nucleus collisions up to a system size of CC reactions. The agreement originates in the solid description of elementary pp collisions. Only for a low kinetic energy around 1 GeV, an underestimation for quasi-free np collisions and subsequently for CC is observed. Overall, the description of low energy collisions is comparable with similar transport approaches. In the current work the dilepton decays are taken into account for the spectral function calculation for all vector meson ($\rho$, $\omega$, $\phi$), leading to contributions from their direct dilepton decays down to $2m_e$ below the hadronic threshold.

The hadronic transport approach is complemented by a coarse-graining approach based on the same hadronic evolution to study the sensitivity of the invariant mass spectrum to in-medium modifications of the vector meson spectral function. Both revealed similar features in their dilepton contributions. Nevertheless, the transport description including the coupling to baryons and collisional broadening cannot account for the necessary significant modifications visible in larger collision systems.
caused by an in-medium description of the vector meson spectral function. The significance of an in-medium description is noticed already for the here investigated low energy collisions beginning with systems as large as ArKCl.

The presented results include predictions for upcoming HADES results for \( \pi \) and AuAu reactions. Comparisons to experimental data of the former specifically probe the coupling of the \( \rho \) meson to the \( N^*(1520) \) baryonic resonance, while the AuAu system is expected to be even more sensitive to medium modifications than the already studied ArKCl collisions indicated by the presented prediction of the coarse-graining approach.

Based on this solid and well-understood baseline for the dilepton production from the hadronic sector for low beam energy collisions in the future the dilepton production in intermediate and high beam energy collisions can be addressed. Dilepton emission from intermediate beam energy collisions is one of the promising observables of the CBM experiment at FAIR. Hybrid approaches allow to explore the high beam energy reactions of RHIC or LHC by a combination of the dilepton radiation from a hydrodynamic calculation with the emission from a hadronic afterburner, where SMASH can be applied as well for the non-equilibrium hadronic evolution.

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Appendix A: Transverse momentum and rapidity spectra for pp collisions at \( E_{\text{kin}} = 3.5 \) GeV

The lepton pair transverse momentum and rapidity from reactions at \( E_{\text{kin}} = 3.5 \) GeV are compared to experimental data from [1] in different invariant mass windows that reflect the different dominant contributions over the invariant mass range. Below 150 MeV the \( \pi \) Dalitz decay dominates. Between 150 MeV and 470 MeV the \( \eta \) decay is the largest contribution, while above 470 MeV and below 700 MeV the \( \rho \) channel exceeds the others. Above 700 MeV the \( \omega \) peak is dominant. The plots in Fig. 23 and Fig. 24 show that also for those more differential spectra that probe specific channels and different kinematic observables that probe different regions of the phase space agreement with experimental data is reasonable.

Appendix B: Invariant mass spectra for pNb collisions for two momentum windows at \( E_{\text{kin}} = 3.5 \) GeV

Two invariant mass spectra are presented in Fig. 25 for two different dilepton momentum windows (0 < \( p_{ee} \) < 800 MeV and \( p_{ee} > 800 \) MeV). The underestimation of the shoulder at 500 MeV (also seen in Fig. 12) is observed for the smaller momentum dileptons (\( p_{ee} < 800 \) MeV), the \( \phi \) peak, however, matches the experimental data for both momentum windows. Overall both are in reasonable agreement with experimental data [18], too.

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FIG. 23. Transverse momentum spectra of dielectrons produced by pp collisions at $E_{\text{Kin}} = 3.5$ GeV in different invariant mass windows. Experimental data from [17].

FIG. 24. Rapidity spectra of dielectrons produced by pp collisions at $E_{\text{Kin}} = 3.5$ GeV in different invariant mass windows. Experimental data from [17].

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FIG. 25. Invariant mass spectrum of dielectrons produced by pNb reactions at $E_{\text{kin}} = 3.5$ GeV in different dielectron momentum ($p_{\text{ee}}$) windows. Experimental data from [15].

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