PROCEEDINGS OF SCIENCE

Effective spectral function of the ρ meson via lifetime analysis in hadronic transport

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The melting of vector meson peaks in dilepton measurements is a canonical example of medium effects on strongly interacting matter. In the context of on-shell hadronic transport, where the resonance has a fixed vacuum spectral function, this melting happens dynamically as the medium suppresses dilepton emission by absorbing resonances. In this work, we analyse effective lifetimes of the ρ meson to quantify such collisional broadening within the SMASH approach, for both a thermalized hadron gas and off-equilibrium matter created in heavy-ion collisions.

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1. Introduction

Dilepton measurements display a melting of resonance peaks in electromagnetic (EM) radiation in the hot and dense medium created in heavy-ion collisions (HIC) [2, 3]. In low invariant mass ranges – below 1.5 GeV –, the EM spectral function is dominated by the ρ-meson channel decaying into a lepton pair [4]. Inside a medium, this channel is broadened in comparison to the "vacuum" of $p + p$ collisions, which may be an evidence of chiral symmetry restoration, since this melting brings the spectral function of the vector meson ρ closer to the one of its chiral axial-vector partner a_1 [5].

The low beam energy regime of HICs, where deconfinement might not take place, is well described by hadronic transport approaches. Due to the inelastic interactions of the ρ with the hadrons, there is a decrease in the dilepton emission, since absorbed particles cannot decay[1]; such an effect is commonly referred to as *collisional broadening*. In this work we use the SMASH approach [6], based on the relativistic Boltzmann equation for the evolution of hadrons. It relies only on vacuum properties, hence no a priori knowledge of the medium is present. However, inelastic scatterings still suppress the dilepton emission and consequently modify the spectra, albeit not enough to reproduce experimental yields [7]. To do so, a coarse-graining method is applied, using thermal rates from a full in-medium model [8]. It is therefore of interest, and the goal of this Proceeding, to assess and quantify this *dynamical* broadening that emerges.

2. Collisional broadening

In vacuum, the spectral function of a resonance is described by a relativistic Breit-Wigner distribution

$$\mathcal{A}(m) = \frac{2\mathcal{N}}{\pi} \frac{m^2\Gamma(m)}{(m^2 - M_0^2)^2 + [m\Gamma(m)]^2}, \tag{1}$$

where M_0 is the pole mass and $\Gamma(m)$ is the mass-dependent vacuum decay width [6]. Upon the creation of a resonance in SMASH, its mass is sampled from this distribution convolved with kinetic factors, and is constant throughout the evolution, in which the particles are always *on-shell*. This is in contrast to some other transport approaches [9, 10], where the collisional broadening is explicitly taken into account during the propagation.

Since Γ is simply the rate of decay in vacuum, the dynamical broadening in SMASH can be readily quantified by defining the analogous *effective width* as inverse mean lifetime in the proper frame:

$$\Gamma^{\text{eff}}(x) = \frac{1}{\langle\tau\rangle_x} = \left\langle \frac{\gamma}{t_f - t_i} \right\rangle_x, \tag{2}$$

where γ is the Lorentz factor and $t_{i,f}$ are the resonance initial and final times, i.e. when it is created and destroyed, either by decay or absorption. The subscript x highlights that the average on the r.h.s. can be computed differentially, for a x-dependent effective width. Naturally, this is larger than the vacuum decay, so replacing $\Gamma \to \Gamma^{\text{eff}}$ in (1) corresponds to a broadened *dynamic* spectral function $\mathcal{A} \to \mathcal{A}^{\text{dyn}}$.

[1]In practice, SMASH shines dileptons continuously until the absorption due to the inelastic interaction.

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3. Results

3.1 Matter in equilibrium

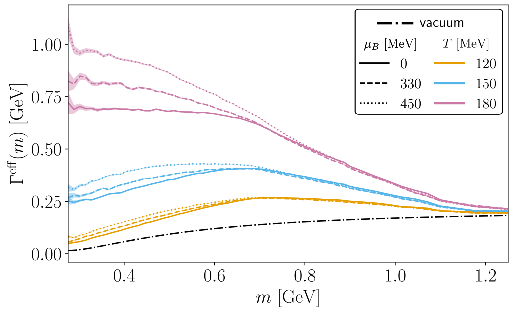

Figure 1: Effective width of the ρ meson in a thermalized system. The legend shows the initial values of T and μ_B, slightly larger than the actual values after relaxation.

The mass-dependent effective width of ρ mesons is shown in Fig. 1 in an equilibrated hadron gas under different thermodynamic conditions. A box is initialized with thermal multiplicity and momentum distributions with an input value of temperature T and baryochemical potential μ_B, and allowed to relax for 10^3 fm, which is sufficient for thermalization. Generally, an increase in either T or μ_B leads to a larger width of the ρ meson, since collisions are more likely when the energy density is greater. As the cross sections for $2 \to 1$ and $2 \to 2$ processes in this energy range decrease with the masses of incoming particles, higher mass ρ mesons are rarely absorbed, and so suffer little to no broadening. In general, the finite temperature T affects the whole distribution, while μ_B only changes ρ mesons with masses smaller than $M_0 = 0.776$ GeV. This relates to the favoring of baryons – nucleons and nucleonic excitations –, suggesting that their couplings to the ρ dominate the low-mass region.

The corresponding dynamical spectral function is shown in Fig. 2. The denominator of (1) suppresses the μ_B effects, since they are present only for masses away from the pole. Also shown in the figure is the full in-medium model calculation [8], integrated over the full momentum range for a meaningful comparison. The qualitative behavior is similar, with the ρ melting as temperature increases and gaining a small positive shift in the pole mass. However, there are noticeable quantitative differences; namely, the broadening is stronger in the full in-medium model, with a larger high-mass tail and a flatter low-mass tail. This is due to the "tree-level" character of hadronic transport: in SMASH, quantum corrections are only taken into account for a vacuum, via the matching of elementary cross sections to experimental data, so (for example) the dressing of loops in the ρ self-energy is not present as it is in the full in-medium model.

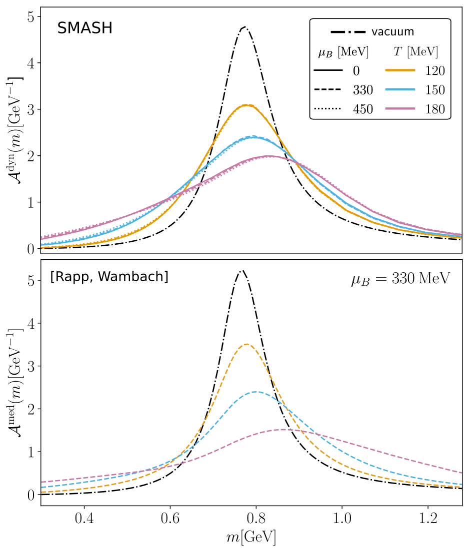

Figure 2: Spectral functions for a thermal hadron gas. (Upper) Dynamical calculation with the effective width (2) and (lower) from the Rapp-Wambach full in-medium model.

3.2 Nuclear collisions

We also study the emergence of collisional broadening in the out-of-equilibrium matter created in low beam energy HICs, for which hadronic transport is well-suited. The effective width is shown in Fig. 3.

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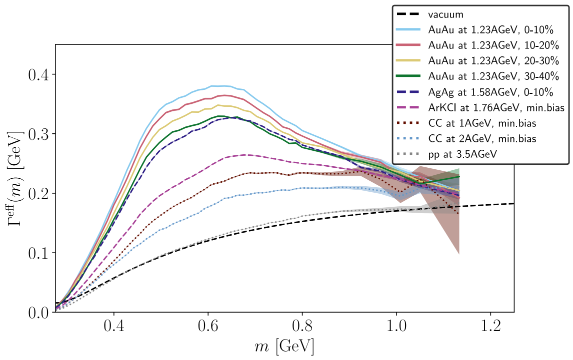

Figure 3: Effective width of the ρ meson in different collision systems with fixed-target energies.

The effective width displays a clear dependence on system size, increasing with heavier ions and more central collisions. Intuitively, a $p + p$ collision mimics the vacuum, in which no broadening arises. However, system size does not describe the whole picture: the width for a $30 - 40\%$ Au + Au collision has approximately the same mass-dependence as a central Ag + Ag, even though the latter has $\sim 50\%$ more participants (93 against 140, on average). Furthermore, unlike in the equilibrated hadron gas scenario, the width for masses close to the hadronic threshold is small for all systems.

Equation (2) can also be computed differentially with respect to the birth time of the resonance. This is shown in the left of Fig. 4 and corresponds to a cronometer for the medium itself, as it determines for how long the particles created at t_i will propagate until it decays or is absorbed. It highlights the distinction between the similar mass-dependent widths: the Ag+Ag system has more participants, so the *initial* broadening is larger than in the $30 - 40\%$ Au+Au. But they also collide with a slightly higher beam energy – not enough to enter the high-$\sqrt{s}$ regime –, so the medium disperses faster so that the time-integrated widths are equal. This cronometer also explains why small masses in Fig. 3 show no broadening: they are mostly produced later in the evolution, when the matter is already dilute, so that on average they effectively propagate in vacuum. In this dilute stage, the effective width is equal to the vacuum decay width, which is below Γ_0 because the average mass is smaller than M_0.

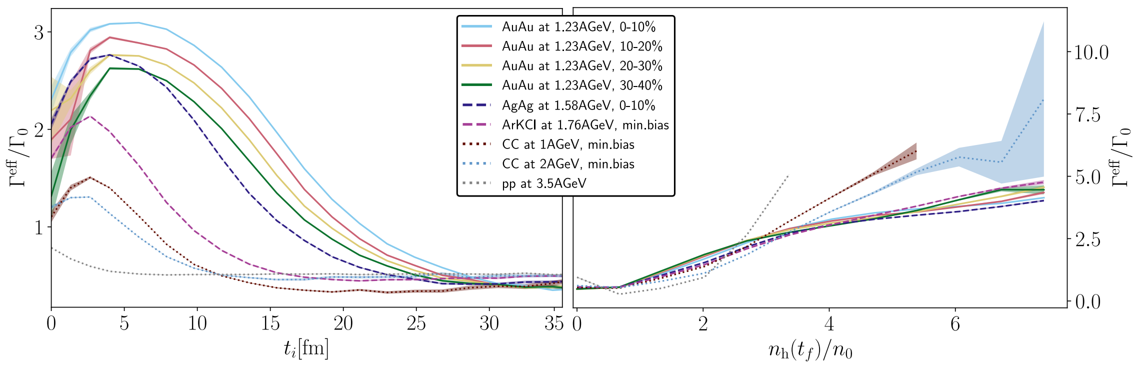

Figure 4: Mass-integrated effective width, normalized by the decay width at pole mass $\Gamma_0 = 0.149$ GeV. (Left) Evolution of $\Gamma^{\rm eff}$ computed by fixing the birth time. (Right) Dependence on the local density at the final interaction.

The previous considerations point to a monotonic dependence on the local density, as shown in the right plot of Fig. 4. A near universal curve appears, reminiscent of the explicit collisional broadening input to off-shell models. For simplicity, we use the hadron density at the final interaction as a proxy for the density across the particle propagation, as it is readily available from the collision history, but the selected time or type of density has no significant impact on this universal behavior.

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Some deviations occur for p+p and C+C collisions because the density calculation starts to break down, as these systems do not reach these high densities.

4. Conclusions

We quantify the dynamic collisional broadening that the ρ meson undergoes within the SMASH approach, by computing the effective total width as the inverse mean lifetime. We do this for a hadron gas in equilibrium, finding a similar qualitative behavior to a full in-medium model; and for the expanding matter created in HICs, where we found an universal dependence on the local density; further analyses are performed in [1]. An interesting future work regards the fate of the absorbed ρ mesons, by studying the specific channels that contribute to the broadening and the sensitivity to different collections of particle species.

5. Acknowledgments

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