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Hadron resonance production and final state hadronic interactions with UrQMD at LHC

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Abstract. We discuss the effects of the final hadronic state, in ultra-relativistic nuclear collisions, on hadronic resonance properties and measurable production rates. In particular we will compare our results with recent ALICE data on resonance production. We show that the hadronic phase of the system evolution has a considerable impact on the measured resonance ratios and p_T spectra. We also discuss some of the remaining uncertainties in the model and how they may be addressed in future studies.

1 Introduction

The formation of a Quark Gluon Plasma (QGP) in ultra-relativistic nuclear collisions is a feature that has been observed at experiments at the Relativistic Heavy Ion Collider (RHIC) [1–4], the Large Hadron Collider (LHC) and likely also occurs at the Super Proton Synchrotron (SPS) at CERN. Current focus in QGP physics is on the determination of the properties of this newly found state of matter. As the quarks and gluons themselves are not directly observable, due to the confinement feature of Quantum-Chromo-Dynamics (QCD), one has to rely on suitable transport models to disentangle the connection between experimental data and the properties of the produced state of matter. An approach which has recently proven successful, in describing the data, is the application of viscous fluid dynamics (see e.g. [5–10]), where the equation of state (EoS) and the viscous coefficients can be implemented in a straightforward way. Despite its success, recent results from LHC and SPS data suggest that measured hadron properties may be changed after the produced system has left a state of local chemical equilibrium [11, 14–16]. In this final phase of the systems expansion, hadrons are expected to be the relevant degrees of freedom. So called hybrid models therefore aim to describe this phase with a microscopic transport treatment based on the (re-)scattering of hadrons according to measured or calculated cross sections.
As hadronic resonance creation is the most important contribution to the hadronic re-scattering one expects that the study of these resonances, in nuclear collisions, can help to understand the final stage of the collision. In this work we will discuss results, of such an hybrid model, on hadronic resonance creation in ultra-relativistic nuclear collisions. In particular we want to find out how the hadronic phase influences resonance spectra and how well constrained the description of the hadronic phase is [12, 13].

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2 Hadronic final state in the UrQMD hybrid model

For our study we employ the UrQMD hybrid transport model in its newest version [17–20] (v3.4). The UrQMD hybrid model combines the advantages of a hadronic transport model with an intermediate hydrodynamical stage for the hot and dense phase of a heavy ion collision. It consists of the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model which is used to generate the initial state for a full (3+1)-dimensional ideal hydrodynamical evolution [21, 22] to simulate the medium expansion. The process which translates the fluid dynamical fields to discrete particles is called 'particlization'. this 'particlization' occurs on an iso-energy density hypersurface. We use the Cornelius hypersurface finder [23] to determine this surface, used as input to the Cooper-Frye prescription [24], which is then sampled in accordance with the conservation of important quantum numbers like energy, baryon number, strangeness and electric charge. In the present work we assume this 'particlization' occurs at a constant energy density hypersurface of $\epsilon = 3.5\epsilon_0$ (corresponding to a switching temperature of 165 MeV), where ϵ_0 is the nuclear ground state energy density. After the particles are produced they are propagated again within the UrQMD model, where the interactions of the hadrons are taken into account. The current version of UrQMD includes binary elastic and $2 \to n$ inelastic scatterings, including resonance creations and decays, string excitations and particle + anti-particle annihilations. The cross sections and branching ratios for the corresponding interactions are taken from experimental measurements, where available, and detailed balance relations.

In this work we will present results for collisions of lead ions at the center of mass beam energy of $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV as for the ALICE experiment at the LHC. All the following results and data presented will refer to this beam energy and colliding system.

During the final hadronic phase the model allows us to follow the space-time evolution of every hadron, including the resonances. We can therefore extract the properties of the resonance production at any point in time after the 'particlization' has occurred. In the following we discuss resonance properties at several different steps in the time evolution of the system. The first is the point at which 'particlization' takes place. At that point in (space and) time hadrons are produces according to a thermal momentum distribution of fixed temperature. After that time, these momentum distributions might change due to the hadronic state interactions. Since experiments have to reconstruct the resonances from their decay products, which again could have re-scattered in the hadronic phase, we have to define what we call an 'observable resonance'. In this study we define such an 'observable resonance' as a resonance whose decay products have not re-scattered at all, elastic or inelastic, during the hadronic phase. One should note that this definition is not exactly identical with the method used in experiments, where resonances are normally detected by the invariant mass spectrun of their decay products. The measured invariance mass spectrum might contain decay products which have scattered with a small momentum transfer, but such a correction is of the order of 10%.

As a first step we study, for different resonances, the likelihood of it being an observable resonance. For this we show the ratio of the p_T distributions for different resonances, the ρ^0, K^{*0}, ϕ and $\Lambda(1520)$, for most central collisions ($b < 3.4$ fm) in the left hand side of figure 1. The ratio depicted is that of all resonances, decaying during the hadronic phase, over all observable resonances as defined above. The resulting ratio then serves as an indicator for the number of generations (decay and regeneration) of a certain resonance, during the time evolution of the hadronic phase. As one can clearly see this ratio depends strongly not only on the resonance considered but also on the transverse momentum of the resonance. This is result is rather expected. The resonances with short lifetime, like the ρ, decay while the system is still dense and its decay products are more likely to re-scatter. The same is true for resonances with small momenta. Their decay products take longer to traverse

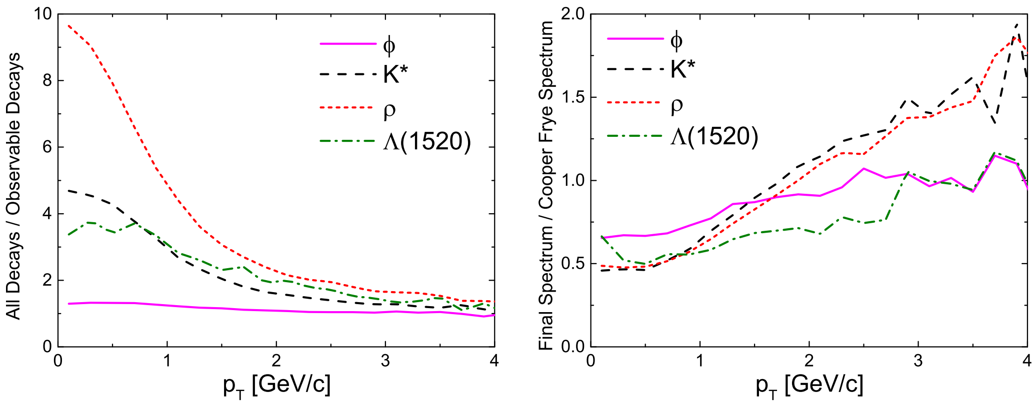

Figure 1. Left: Ratio of decaying over observable resonances, as function of transverse momentum, for different resonances, the ρ, K^*, ϕ and $\Lambda(1520)$, for most central Pb+Pb collisions ($b < 3.4$ fm) at $\sqrt{s_{\rm NN}} = 2.76$ TeV. Right: Ratio of all observable over all produced ρ, K^*, ϕ and $\Lambda(1520)$ (at the particlization hypersurface) for the same system.

and leave the system and therefore are more likely to re-scatter.

This result poses the question whether resonances with large transverse momentum can be regarded as 'messengers' from the particlization, i.e. the surface at which the hadrons are born. To give an answer we show in the right-hand side of figure 1 the ratio of the p_t spectra of observable (final) resonances over the one at particlization. All resonances show a clear dependence on the transverse momentum, which indicates that while resonances at large p_T are more likely to be observed they do not fully reflect the properties of the system at particlization.

As figure 1 clearly points out, the spectra and abundance of hadronic resonances in the model are strongly affected by the hadronic final state interactions. It would be very helpful if these effects can be confirmed by experimental measurements. A particularly interesting observable for this is the centrality dependence of the ratios of resonances to their stable daughter particles. As the systems surface to volume ratio increases for more peripheral collisions one would expect the final state effects to be less severe for more peripheral collisions. We therefore extracted the ratios of K^{*0}/K^-, ϕ/K^-, ρ^0/π^-, Λ^*/Λ and Σ^{*+-}/Λ, as a function of centrality, from the UrQMD hybrid model. The results are shown in figure 2 as solid lines. We also compare our results with experimental data from the ALICE collaboration [25] and results from a centrality independent thermal fit to ALICE data [26].

Our simulations appear to describe the available data rather well. While the K^*/K^- shows a strong centrality dependence the ϕ/K^- does not so. This can be understood as a result of the different lifetimes of the K^* and ϕ. While the ϕ has a long lifetime and decays mainly outside the fireball, the K^* decays within the high density hadronic phase and its decay daughters are therefore more likely to re-scatter. As the ρ also has a rather short lifetime, its centrality dependence is similar to that of the K^*. An interesting observation can be made about the ratios of the baryonic resonances Σ^* and Λ^*. Their ratios do not show such a strong centrality dependence as observed for the mesonic resonances, even though their lifetimes are significantly shorter than that of the ϕ. A possible explanation could be the rather large cross section for the regeneration of such a baryonic resonance, even at small relative

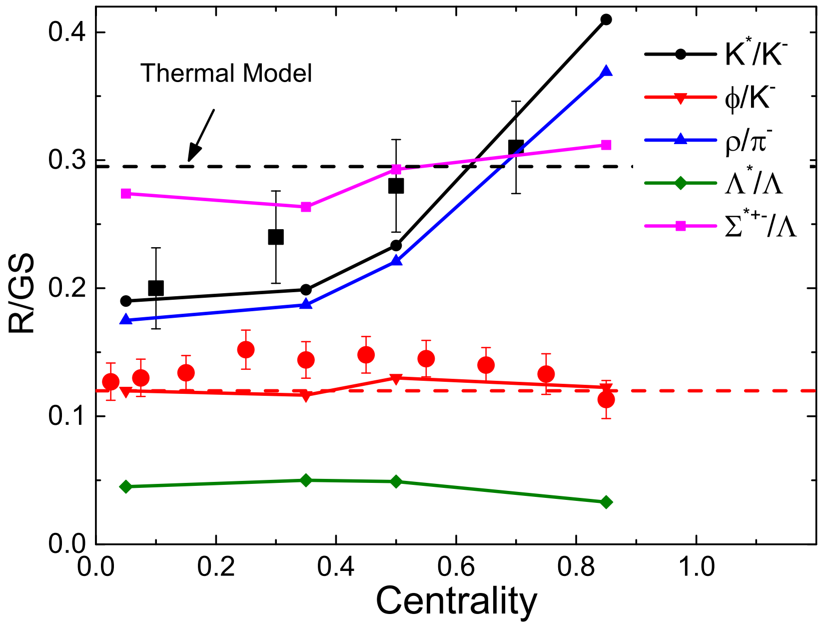

Figure 2. Resonance over ground state (R/GS) ratios of several 'observable' (as defined in the text) hadronic resonances, as a function of centrality. We present our results for Pb+Pb collisions in different centrality bins, as defined in [25], at $\sqrt{s_{\rm NN}}$ = 2.76 TeV. The data are from [25] and thermal fit from [26].

momenta of the daughter particles, which would lead to a long period of resonance regeneration and therefore to a higher probability to reconstruct a baryonic resonance. Confirming such a scenario will be work for future investigations.

The ϕ meson is particularly interesting because of its long lifetime and high chance of being reconstructed. Furthermore the mass of the ϕ is very similar to that of the nucleon. In systems which are essentially net baryon free, like those produced at the LHC, this means that, when thermal production of hadrons is assumed, the ϕ should show spectra very similar to that of the nucleon. It was therefore proposed, that the ϕ/p ratio might be an indicator for the degree of thermalization, at the point of hadron production, in nuclear collisions. The ALICE experiment has recently published data on that ratio [25], which is shown in figure 3 (left), together with results from our model. In this figure we can see how the p_T dependent ratio changes with centrality. While it is almost flat for the central events it shows a clear decrease with p_T for peripheral collisions. The UrQMD hybrid model, shown as solid lines, does reproduce the trend of the data, however the ϕ/p ratio for central collisions shows even an increase in p_T while the data remain flat. If we compare the final ratio (red solid line) with the one obtained directly at particlization, we can see that the hadronic final state appears to improve the agreement with the data at least for small $p_T < 2$ GeV/c.
To understand the origin of the shape change of the before mentioned ratio we have to investigate the p_T spectra of protons and ϕ's separately. This is done in figure 3 (right). There we compare the p_T spectra of protons (blue) and ϕ (magenta) after the hadronic phase (solid lines) and at particlization

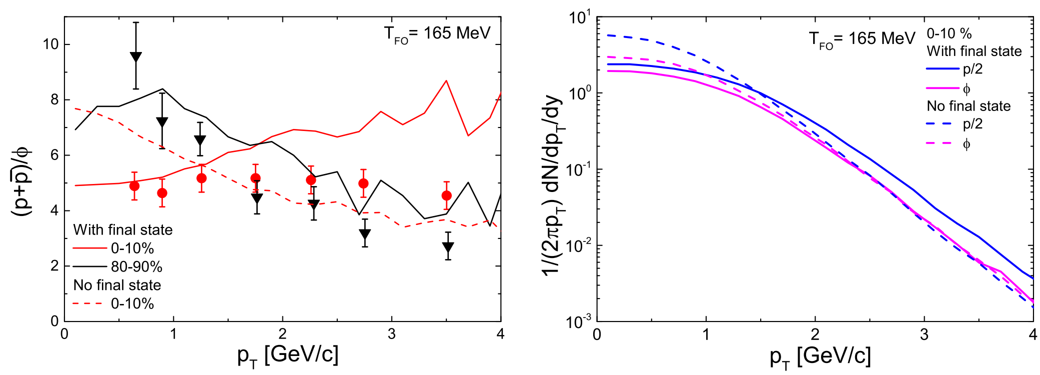

Figure 3. Left: Ratio of protons and anti-protons over ϕ, as a function of transverse momentum, for two different centrality bins. We compare our results with (solid line) and without (dashed line) the hadronic final state with experimental data from the ALICE collaboration [25]. Right: Final spectra (solid line) and spectra at particlization (dashed line) for protons (blue curves), which includes resonances decays and ϕ (magenta curves), for most central collisions $(0-10\%)$.

(dashed lines). Note that the proton spectra are devided by their spin degeneracy factor to compare with the ϕ spectra. One would naively assume that at particlization the spectra of both particles should be almost identical, as they are produced according to thermal distributions with the same temperature. However we already observe differences at this early time when we include the decay of resonances. While at large transverse momenta, the spectra appear identical, the protons have a larger contribution at lower momentum $p_T < 1$ GeV/c. The reason for this excess are resonance contributions to the protons. There are many resonances which can decay into a proton no such states are implemented which could decay into the ϕ. So already these resonance contributions to the proton spectra would make the p/ϕ ratio decrease with transverse momentum. When comparing the spectra of the ϕ, before and after the re-scattering we only observe a mild reduction of the ϕ's at lower momenta, due to the re-scattering of the decay products. The ϕ does not seem to acquire any significant radial flow in the final state. The proton spectrum on the other hand changes significantly not only being suppressed at low p_T but also being enhanced at large momenta, as expected for a gain of radial flow of the protons.

3 Uncertainties

As discussed above the UrQMD hybrid model appears to give a good qualitative and quantitative description of the hadronic re-scattering in ultra-relativistic nuclear collisions. Of course not only the presented observables are sensitive on the final state hadronic re-scattering. As discussed in other publications [11, 14–16, 27] also the abundances and properties of stable hadrons may be changed by hadronic interactions. It is therefore clear that one desires a most accurate description of the hadronic interactions to be able to interpret any data taken for example with the ALICE experiment. On the other hand many aspects of hadronic interactions are still not known. Many elementary cross sections for example are simply not measured and therefore a possible source of shortcomings of our approach. In the following we will discuss an example of such an uncertainty of the hadronic re-scattering and discuss how it may be constrained to further improve the description of the hadronic re-scattering phase.

Table 1. Branching ratios (in %) for different resonances into Λ+K and Σ+K, implemented in the current version of UrQMD (I). Orange: Large errors on the branching ratio [28]. Red: No information available from the particle data book. II: Parameter set with unknow branching ratios set to zero, to estimate systematic uncertainty.

Ratio [%]	$\Gamma_{\Lambda K}/\Gamma_{tot}[\%]$		$\Gamma_{\Sigma K}/\Gamma_{tot}[\%]$	
Resonance	I	II	I	II
N*(1650)	7	7	2	2
N*(1710)	10	10	3	3
N*(1720)	10	10	2	2
N*(1900)	2	2	0	0
N*(1990)	3	3	0	0
N*(2080)	12	0	0	0
N*(2190)	12	0	0	0
N*(2220)	12	0	0	0
N*(2250)	12	0	0	0
Δ(1920)	0	0	3	3
Δ(1930)	0	0	15	0
Δ(1950)	0	0	12	0

Table 1 shows the branching ratios of different baryonic resonances, decaying to hyperon+Kaon, implemented in UrQMD. While many of them are known [28] some of them have large errors (orange) and some branching ratios are even entirely unknown (red) and have to be estimated. On the other hand we expect these branching ratios to have some effect on observable properties of hyperons and kaons, especially in systems which are dominated by hadronic interactions. We compared the standard parametrization of these cross sections (I) with one which removes all the unknown decays into hyperon+K (II) by simulating a set of fixed target events for Ca+Ca collisions at an beam energy of $E_{\mathrm{lab}} = 1.76$ A GeV. For these systems we can compare the resulting m_T spectra for cases I and II with data from the HADES collaboration [29–31]. The results are shown in figure 4 where the solid line depicts the case I and the dashed lines case II. From the comparison one can clearly see the large impact of the branching ratios on the resulting m_T. It appears that case II gives a better description of the data, i.e. the branching ratio for N* and Δ* into hyperon+Kaon appear to be small, however we can not include different decays which involve also other daughter particles like additional pions. A useful next step would be now to try and constrain the resonance properties and decay branching rations from more elementary data, e.g. p+p or π+N collisions at beam energies which lead to resonance excitations. Only when these elementary processes are better understood we can continue interpreting the data of the more complex nuclear collisions.

4 Summary

In summary we have discussed the effects of the final hadronic phase on resonance properties in ultra-relativistic nuclear collisions at the LHC, as measured with the ALICE experiment. We have found that the hadronic re-scattering, only with known cross section by itself leads to significant modifications of the resonance spectra and describes well the measured yields and properties of resonances measured by ALICE. Final state hadron yields, ratios and spectra do not reflect the properties of the system at particlization. However, unknown hadronic interactions pose a problem as they increase the

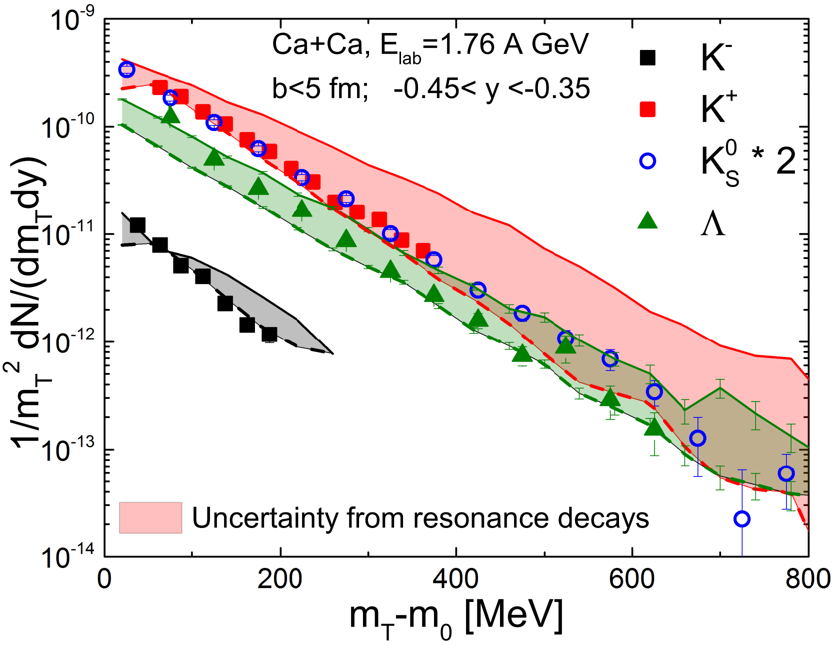

Figure 4. Transverse mass spectra for collisions of Ca+Ca at fixed target beam energy of E_{lab} = 1.76 A GeV with an impact parameter of $b < 5$ fm. We compare the m_T spectra of several strange particles, using either UrQMD with branching rations I (solid line) or II (dashed line), with experimental data from HADES [29–31].

degree of uncertainty in the simulations. We have shown how these uncertainties have severe consequences on the description of strange particle spectra at low beam energies, where most of the systems evolution occurs in a hadronic phase. We suggest that an improved understanding of elementary reactions, like p+p and π+N, is essential also for the understanding and interpretation of ultra relativistic nuclear collisions at the LHC. The description of the hadronic phase is an interesting problem that connects the results of experiments at beam energies 3 orders of magnitude apart (GSI to LHC).

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