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Studying chiral partner resonances K^* and K_1 to investigate chiral symmetry restoration with ALICE

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In the relativistic heavy-ion collisions, the quark-gluon plasma (QGP) is produced during the deconfinement phase transition, when the system reaches a specific temperature (T_{ch}) and energy density. At about the same temperature, $T_{ch} \sim 156$ MeV, and at approximately zero baryon chemical potential μ_B, lattice QCD calculations indicate that chiral symmetry (CS) restoration occurs. CS restoration can be investigated using parity partner resonances, particles that have the same quantum numbers except parity, such as $K^*(892)^0$ and $K_1(1270)$. In the vacuum these resonances exhibit different masses, decay lengths, and production yields. However, at a temperature close to that associated with CS restoration, these differences are expected to diminish, resulting in a K_1 to K^* production ratio higher than the one predicted by the statistical hadronization model. The ALICE Collaboration has already measured K^* production spectra using LHC Run 2 data, evaluating the K^*/K yield ratios in pp, p-Pb and Pb-Pb collisions, providing an experimental evidence that $K^*(892)^0$ decay products undergo rescattering during the hadronic phase of the QGP evolution. The reconstruction of the K_1 resonance has not been achieved yet, but it will be accessible using Run 3 data.

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1. Introduction

The QGP produced in high-energy heavy-ion collision is characterized by an initial hydrodynamic evolution and cooling phase, that then leads to hadronization. With further cooling, the chemical freeze-out temperature of $T_{ch} \simeq 156$ MeV is reached, at which point inelastic interactions among the hadrons cease. Subsequently, the system reaches the kinetic freeze-out temperature, where elastic interactions between hadrons also stop [1, 2]. The time interval between the chemical and kinetic freeze-out temperatures is referred to as the hadronic phase.

Resonances, short-lived particles that decay via the strong interaction, are good probes for studying the hadronization mechanisms of the QGP and the hadronic phase of the collision. Their lifetimes are comparable to the timescale of the hadronic phase evolution from its formation to kinetic freeze-out. If a resonance decays before the kinetic freeze-out, its decay products may undergo rescattering with other hadrons [3]. Rescattering alters the momenta of the decay products, either preventing the reconstruction of the resonance or broadening the measured invariant mass distribution. Consequently, this process reduces the observed resonance yield. On the other hand, pseudoelastic interactions within the hadronic medium can regenerate resonances [4], leading to an enhancement of their yield. In the following sections recent results obtained on K^* resonance production and future plans on the investigation of chiral symmetry restoration using chiral partner resonances will be discussed.

2. Chiral symmetry restoration

In regular nuclear matter, chiral symmetry (CS) is broken due to quark masses, which result from spontaneous symmetry breaking. Lattice QCD calculations predict that CS restoration occurs during the phase transition to the QGP near the chemical freeze-out temperature, T_{ch} [5]. Experimentally, CS restoration can be studied by analyzing chiral partner resonances, that have the same quantum numbers except for parity. When CS is broken, there is a difference in mass and in the production yields between chiral partners. However, near T_{ch} when CS is approximately restored, the masses of chiral partners, and consequently their production yields, are expected to become nearly degenerate.

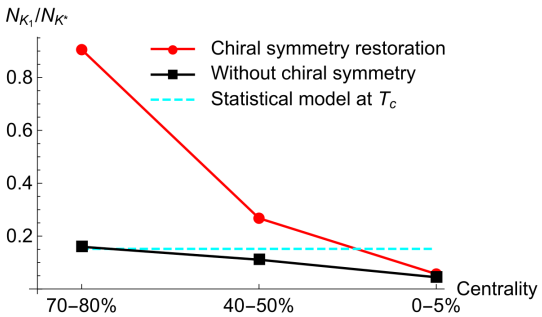

Figure 1: The theoretically predicted yield ratio of K_1 to K^* in the presence and absence of chiral symmetry restoration for centrality classes of 70-80%, 40-50%, and 0-5% in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 5$ TeV. Figure taken from [6].

As can be seen in Fig. 1, CS restoration can be studied looking at the ratio between the production yields of chiral partners as a function of the centrality of the collision. In particular,

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good candidates for this study are the K_1 and the K^* resonances. Theoretical predictions [6] indicate that, if CS is restored, an enhancement of the K_1/K^* ratio is expected to be observed in peripheral collisions, in contrast with the statistical hadronization model which predicts a constant ratio as a function of centrality. This effect should be observed in peripheral collisions due to the shorter lifetime of the hadronic phase and consequently the smaller rescattering and regeneration effects, compared to central collisions.

The measurement of the K_1/K^* yield ratio in both pp and Pb-Pb collisions using LHC Run 3 data with ALICE is planned. While the K_1 has not been previously reconstructed by ALICE, the K^* has been measured using LHC Run 2 data. Some of the key results obtained for the K^* during Run 2 will be discussed in the following section.

3. $K^*(892)^0$ production with ALICE at LHC Run 2

Resonances are reconstructed by tracking and identifying their decay products in order to reconstruct the resonance invariant mass. The tracking is performed via the inner tracking system (ITS) and the time projection chamber (TPC), while the TPC and time of flight (TOF) detectors are used for the particle identification [7]. The $K^*(892)^0$ is reconstructed through its decay into $K^{\pm}+\pi^{\mp}$, with a branching ratio of 66.6% [8]. Due to its short lifetime of 4.16 fm/c, the secondary vertex cannot be resolved from the primary vertex, for this reason the tracks coming from the primary collision vertex are selected. The invariant mass distribution is obtained by pairing opposite-sign $K^{\pm}$ and $\pi^{\mp}$ candidates from the same collision event. To reduce the background, the mixed-event technique is applied, which instead consists in pairing unlike sign $K^{\pm}$ and $\pi^{\mp}$ candidates from different collision events and subtracting the resulting invariant mass distribution from the same event. After background subtraction, the resulting distribution is fitted to determine the resonance yield.

Yield ratios between $K^*(892)^0$, $\phi(1020)$ and the $K^{\pm}$ and $\pi^{\pm}$ mesons are shown in Fig. 2 as a function of the pseudo-rapidity density of charged particles produced in the collision ($dN_{ch}/d\eta$), that is a proxy of the collision system size. These particle ratios obtained for different collision systems are shown in the right panel. The suppression of the K^*/K ratio at high $dN_{ch}/d\eta$ indicates that the K^* decay products are rescattered during the hadronic phase of the collision. Moreover, this suppression indicates that rescattering is dominant over regeneration, that instead would enhance the resonance yield. The trend of this ratio is showing that the suppression is increasing with the system size as expected from the EPOS3 model [9]. The $\phi(1020)$ resonance is not affected by rescattering, as the ϕ/K ratio is nearly constant as a function of the system size. The K^* and ϕ have a lifetime of $\sim$ 4 fm/c and of $\sim$ 50 fm/c [8], respectively. For this reason the ϕ is decaying predominantly outside the hadronic medium and its yield is not affected by rescattering effects.

A lower bound of the time interval between the chemical and the kinetic freezeout is estimated employing the particle ratios shown in Fig. 2 and using the following relation: $[K^{*0}/K]_{kinetic} = [K^{*0}/K]_{chemical} \times e^{-\tau/\tau_{K^{*0}}}$ [10]. In this equation, the ratio at the chemical freezeout is fixed at the value obtained at low multiplicity pp collisions, while the value at the kinetic freezeout is the one obtained in all other cases. $\tau_{K^{*0}}$ is the K^* mean lifetime. The results in Fig. 2 show an increase of the lifetime of the hadronic phase as a function of the system size, as expected. The value of the lifetime of the hadronic phase obtained in this way is between 4 and 7 fm/c in central Pb-Pb

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collisions. That is close to the K^* lifetime and indicates that the resonances are a good probe to study the evolution of the hadronic phase.

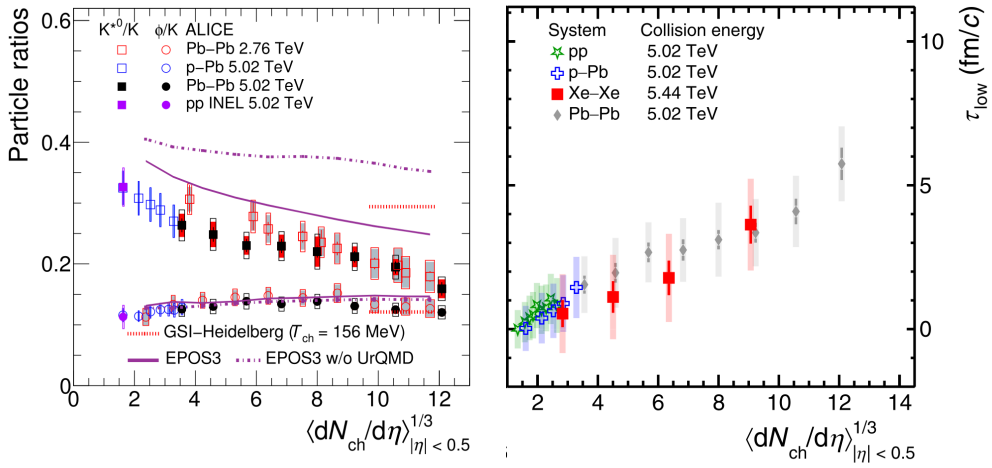

Figure 2: Left panel: $K^*(892)^0$ $/K^{\pm}$ and $\phi/K^{\pm}$ yield ratios as a function of the number of charged particles per pseudo-rapidity of the collision $dN_{ch}/d\eta$. Figure taken from [11]. Right panel: estimated lifetime of the hadronic phase for different collision system and system sizes. Figure taken from [10].

4. Plans for the analysis of K^* and $K_1(1270)$ with ALICE Run 3 data

The ALICE detector has been thoroughly upgraded for Run 3 [12]. The upgrade included an upgraded TPC, a new ITS composed of 7 layers of silicon pixel sensors, a new Fast Interaction Trigger (FIT) made of 5 arrays of Cherenkov radiators and scintillators. Moreover, at the LHC Run 3 a much larger minimum bias data sample has been collected: $\sim 10\times$ Run 2 events of Pb-Pb collisions and $\sim 50\times$ Run 2 events of pp collisions. The TPC and TOF detectors are able to identify particles in a momentum range of [100 MeV, 3.5 GeV] at much higher interaction rates ($\sim$ 50 kHz), while the ITS has a much higher resolution on the impact parameter, which is improved by a factor $\sim$ 5 with respect to Run 2.

Regarding the $K^*(892)^0$ reconstruction using Run 3 data, the invariant mass distributions in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.36 TeV and in pp collisions at $\sqrt{s}$ = 13.6 TeV are obtained, as shown in the plots in Fig. 3. These distributions are fitted with a non relativistic Breit-Wigner to describe the signal and a third degree polynomial to model the residual background. This fit is repeated in different $p_{\rm T}$ and centrality or multiplicity intervals in order to extract the raw K^* yield. The computation of the spectra as a function of $p_{\rm T}$ and centrality can be retrieved applying the corrections for detector inefficiencies and the branching ratio factor of the considered decay channel.

The $K_1(1270)$ resonance has high mass of $\sim$ 1250 MeV and large width of $\sim$ 90 MeV [8]. Therefore, a good resolution and wide identification range of particle momenta is needed and the measurement will be accessible using Run 3 data. The employed decay channel is $K^* + \pi^{\pm}$, so the final state particles are $K^{\pm} + \pi^{\mp} + \pi^{\pm}$. This resonance was never measured in heavy-ion collisions, but was characterized by the Belle2 experiment in e^+e^- collisions [13]. In this system

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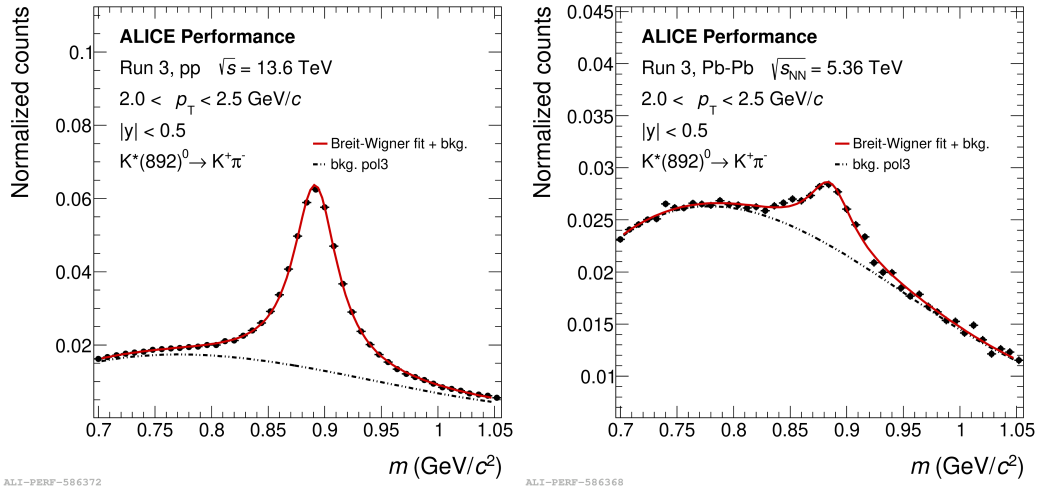

Figure 3: Invariant mass distributions of $K^*(892)^0$ in pp collisions at $\sqrt{s}$ = 13.6 TeV (left panel) and in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.36 TeV (right panel).

QGP is not formed, therefore, it is not suitable for studying CS restoration. However, the Belle2 measurement shows that there are several resonances decaying into $K^\pm + \pi^\mp + \pi^\pm$ and this makes the reconstruction of $K_1(1270)$ very challenging.

ALICE plans to reconstruct $K_1(1270)$ using Run 3 data, and a very high background is expected, both combinatorial and correlated ones. In order to reduce the background, the use of machine learning techniques is planned, e.g. the employment of a boosted decision tree classifier on different variables characterizing the decay products and their topology. To further reduce the background deep neural networks can also be considered.

5. Summary

Resonances are a useful probe for studying the properties of the hadronic phase in heavy-ion collisions. Results from the ALICE experiment using LHC Run 2 data show that the suppression of the K^*/K ratio increases with the system size, indicating the dominance of rescattering over regeneration in the hadronic phase for this resonance. The estimated lifetime of the hadronic phase, ranging from 4 to 7 fm/c in central Pb-Pb collisions, comparable with the lifetime of the K^* resonance, confirms the sensitivity of short-lived resonances to the hadronic phase of the collision. Additionally, the discussion about the observation of chiral symmetry restoration through the K_1/K^* yield ratio using Run 3 data has been presented: the invariant mass distribution of the K^* resonance in Pb-Pb and pp collisions has been reconstructed and the K_1 reconstruction is planned thanks to the upgraded ALICE detector for LHC Run 3, and the significantly larger collected data sample.

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