

# Measurement of the neutral and charged $K^*(892)$ mesons in the MPD experiment at NICA

*Dmitry Ivanishchev*<sup>1,\*</sup>, *Dmitry Kotov*<sup>1,2</sup>, *Evgeny Kryshen*<sup>1</sup>, *Mikhail Malaev*<sup>1</sup>, *Victor Riabov*<sup>1,3</sup>, and *Yuriy Ryabov*<sup>1</sup> for the MPD Collaboration

<sup>1</sup>Petersburg Nuclear Physics Institute named by B.P.Konstantinov of NRC «Kurchatov Institute», High Energy Physics Division, 188300 Leningradskaya Oblast Gatchina 1 mkr. Orlova roshcha, Russia

<sup>2</sup>Peter the Great St.Petersburg Polytechnic University, Institute of Physics, Nanotechnology and Telecommunications, 195251, St.Petersburg, Polytechnicheskaya, 29, Russia

<sup>3</sup>National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31 Kashirskoe shosse, Moscow, 115409, Russian Federation

**Abstract.** Measurements of  $K^*(892)$  meson production provide the means to study properties of relativistic heavy-ion collisions. Because of their short lifetimes, the charged and neutral  $K^*(892)$  mesons provide information about the properties of the late hadronic phase due to the presence of rescattering and regeneration effects that can modify resonance yields. The  $K^*(892)$  mesons can also be used to study the various mechanisms that shape particle transverse momentum ( $p_T$ ) spectra, including the collective flow, in-medium parton energy loss and recombination. Measurement of neutral  $K^*(892)$  mesons requires reconstruction of the charged pions and kaons originating from the primary vertex. At the same time, the measurement of charged  $K^*(892)$  mesons involves reconstruction of the weakly decaying  $K_s$  mesons. Simultaneous measurement of the two particles is a way to minimize systematic uncertainties of the corresponding physical studies. We present results of feasibility studies for measurement of the charged and neutral  $K^*(892)$  mesons in the MPD experimental setup in heavy-ion collisions at NICA energies. Results are obtained using full-scale Monte Carlo simulations of the experimental setup.

## 1 Introduction

NICA collider, which is now under construction in JINR, Russia will study the QCD phase diagram in the region of higher baryon chemical potentials and lower temperatures compared to the LHC and RHIC colliders [1]. The MPD is one of two experiments at the NICA collider dedicated to the study of properties of the nuclear matter under extreme conditions [2]. The properties of the medium created in heavy-ion collisions are studied by measuring characteristics of the final state particles. The particle yields, angular distributions and shapes of the  $p_T$  spectra can be affected by the late hadronic phase. As a

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\* Corresponding author: [ivanishchev@mail.pnpi.spb.ru](mailto:ivanishchev@mail.pnpi.spb.ru)

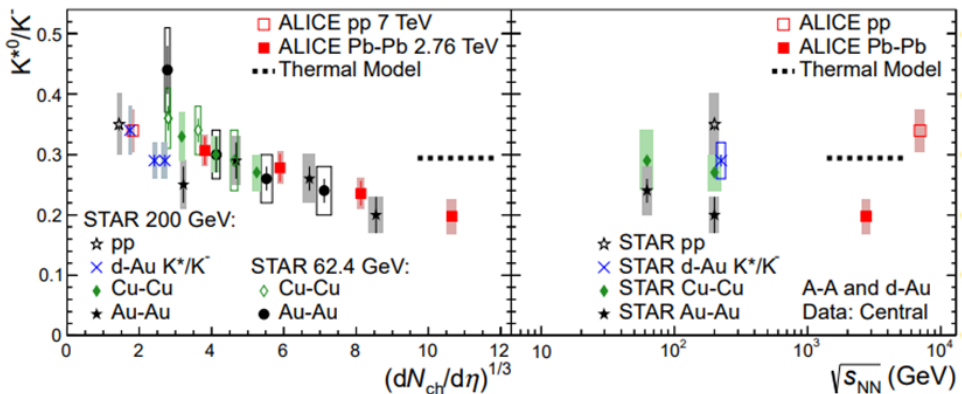
result, model calculations should include simulation of the hadron gas produced in such collisions in order to be compared to real measurements.

The short-lived resonances are traditionally used to study properties of the hadronic phase in different collision systems [3]. The resonances with lifetimes comparable to that of the fireball decay in the evolving system and their daughters undergo rescattering with the surrounding hadrons, thus changing kinematics of decay and preventing reconstruction of the parent particles. At the same time, background hadrons in the hadron gas can recombine and form new resonances. As a result, resonance yields in the final state are defined by their yields at chemical freeze-out, their lifetimes, lifetime of the hadronic phase and its density. This makes resonances a unique tool to study properties of the hadronic phase.

One of the most useful resonances in such studies is  $K^*(892)$  meson, which has a lifetime of  $c\tau \sim 4$  fm/c. Basic properties of this particle are well defined in the PDG [4]. Properties of  $K^*(892)$  mesons measured in heavy-ion collisions carry information about hadron chemistry and strangeness production, reaction dynamics and processes that shape particle  $p_T$  spectra, density and lifetime of the hadronic phase.

Here and throughout this paper the sum of  $K^*(892)^0$  and  $\bar{K}^*(892)^0$ , and the sum of the  $K^*(892)^+$  and  $K^*(892)^-$  mesons are denoted by the symbols  $K^{*0}$  and  $K^{*\pm}$ , respectively, while  $K^*$  denotes  $K^*(892)$  resonance in general.

Properties of  $K^*$  mesons were measured in heavy-ion collisions at RHIC and LHC energies [5]. The ratio of the  $K^*$  meson yields to the yields of the charged kaons is shown in Figure 1. The ratio is shown as a function of the final state charged-particle multiplicity  $dN_{ch}/d\eta$  (left) and collision energy (right) in p+p, d+Au and heavy-ion collisions at  $\sqrt{s_{NN}} = 62,4$  GeV - 7 TeV. The measurements demonstrate that: 1)  $K^*/K$  ratio measured in p+p and p+A collisions does not depend on collision energy in the range  $s_{NN} = 62,4$  GeV - 7 TeV; 2)  $K^*/K$  ratio and hence production of  $K^*$  mesons is suppressed in central heavy-ion collisions. Such suppression is interpreted as a result of rescattering of daughter particles in the hadronic phase [5]. The measurements were used to put a lower limit for the hadronic phase lifetime at RHIC and LHC energies,  $\tau > 2$  fm/c [6]. Measurement of  $K^*$  resonances at NICA will contribute to the systematic study of resonances production in heavy-ion collisions.



**Fig. 1.** Ratios of the yields,  $K^{*0}/K$ , as a function of the final state charged particle multiplicity at midrapidity (left) and collision energy (right) measured at RHIC and the LHC in different collision systems [5].

$K^*$  mesons can also be used to study the baryon-to-meson ratios at intermediate momentum in central heavy-ion collisions at various energies. The ratios are known to be enhanced at RHIC and LHC energies [7] and the observed enhancement is the bulk effect, which is not present in jets [8]. The driving force for the enhancement is not well defined. It

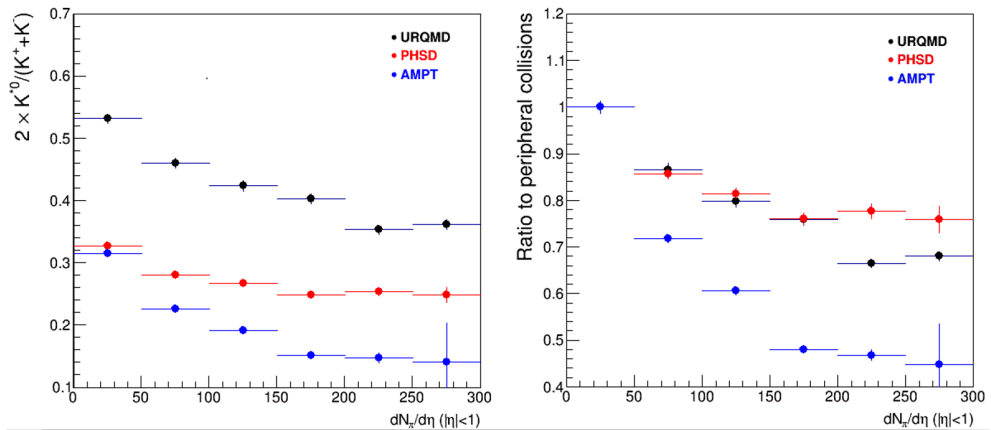
could be a particle mass effect due to the collective radial flow or the quark count effect inherent to recombination models. Measurement of baryon-to-meson ratios for particles of similar masses could provide further constraints for the two competing particle production mechanisms.  $K^*$  meson has a mass, which is very close to mass of proton, which is a baryon. Measurement of  $p/K^*$  ratios at NICA would be very helpful in study of the mechanisms that shape particle spectra at low-to-intermediate transverse momenta.

In this contribution, we review predictions of the most popular event generators for properties of the resonances in heavy-ion collisions at NICA energies and present results of the feasibility studies for reconstruction of  $K^{*0}$  and  $K^{*\pm}$  mesons in the MPD detector.

## 2 Model predictions for $K^*$ resonances production at NICA

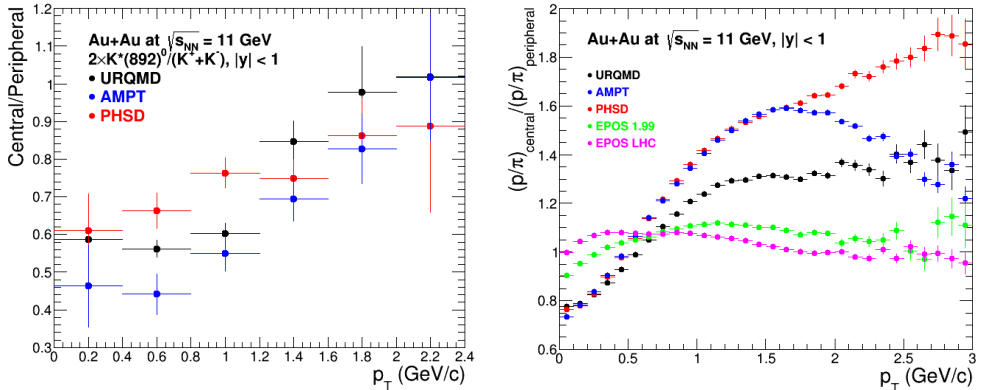
Properties of  $K^*$  resonances produced in Au+Au collisions at  $\sqrt{s_{NN}} = 11$  GeV were estimated with help of UrQMD [9], PHSD [10], AMPT [11] and EPOS [12] event generators. Some of these generators (UrQMD, PHSD and AMPT) can simulate the late hadronic cascades and these were used to estimate the influence of the hadronic phase on the reconstructed properties of the resonances.

The ratios of the yields,  $K^*/K$ , calculated as a function of the final state particle multiplicity are shown in Figure 2 (left). The same ratios were previously studied in heavy-ion experiments at RHIC and the LHC [5]. The ratios normalized to the most peripheral bin are shown in Figure 2 (right). The  $K^*/K$  ratio is suppressed in most central collisions compared to peripheral collisions. Similar suppression was observed at RHIC and the LHC and was interpreted as a result of rescattering of daughter particles in the hadronic phase [5]. The  $p_T$  dependence of the observed modifications for  $K^*$  yields is shown in Figure 3 (left). This is the previously shown particle ratio as measured in central collisions divided by the same ratio in peripheral collisions. The modification of particle spectra occurs at low momentum, just as expected for the effect of the hadronic phase since at lower momentum the particle densities are higher. At higher momenta, the double ratio converges to unity.



**Fig. 2.** Ratios of the yields,  $K^{*0}/K$ , as a function of  $dN_p/d\eta$  calculated by UrQMD (black), PHSD (red) and AMPT (blue) event generators in Au+Au collisions at  $\sqrt{s_{NN}} = 11$  GeV.

The  $p/\pi$  ratio calculated in central Au+Au collisions divided by the same ratio in peripheral collisions is shown as a function of  $p_T$  in Figure 3 (right). One can see that all models predict evolution of the baryon-to-meson ratios with centrality.



**Fig. 3.** Left: the  $K^*/K$  ratios calculated in central collisions divided by the same ratios calculated in peripheral collisions as a function of  $p_T$ . Right: the  $p/\pi$  ratios calculated in central collisions divided by the same ratio calculated in peripheral collisions as a function of  $p_T$ . Calculations are done with the UrQMD (black), PHSD (red), AMPT (blue) and EPOS (green and magenta) event generators for Au+Au collisions at  $\sqrt{s_{NN}} = 11$  GeV.

Model predictions for  $K^*$  meson production significantly differ from each other. However, we can make some general observations. The models predict modifications of the  $K^*$  resonance yields in heavy-ion collisions at NICA energies qualitatively similar to those previously observed at RHIC and the LHC. It means that in heavy-ion collisions at NICA energies, the lifetime and density of the hadronic phase are expected to be large enough. The obtained estimations demonstrate that modification of the particle properties in the hadronic phase needs to be taken into account when model predictions are compared to the experimental results. Measurements of  $K^*$  mesons production can be used to tune the hadronic phase models.

The model predictions for integrated yields, particle ratios, and mean transverse momentum will have to be compared to experimental data to differentiate different model assumptions.

### 3 Feasibility study for reconstruction of $K^*$ mesons

The Au+Au events at  $\sqrt{s_{NN}} = 11$  GeV were simulated using the UrQMD v.3.4 [9]. Particles tracking and detector response were simulated within the MpdRoot framework [2]. The MpdRoot is the official simulation framework of the MPD experiment. The framework is based on the Geant toolkit [13] and simulates the response of the detector subsystems. The corresponding algorithms were developed to reconstruct the charged particle tracks, and signals in the MPD central barrel detectors.

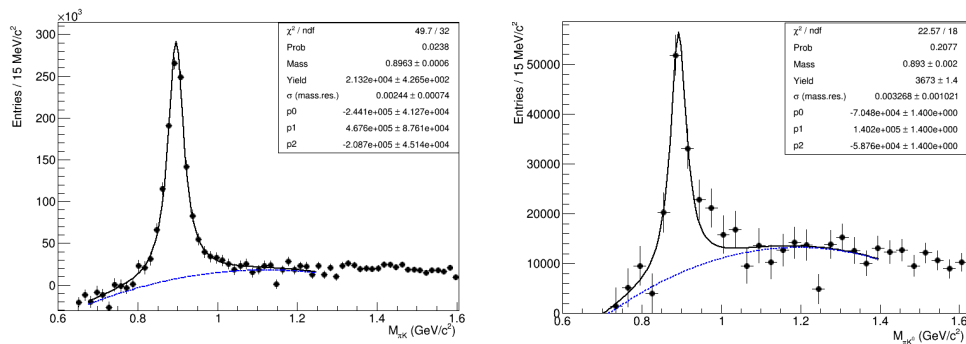
The  $K^*(892)^0$  and  $K^*(892)^\pm$  resonances were reconstructed in the  $\pi^\pm K^\mp$  and  $\pi^\pm K^0$  ( $K^0 \rightarrow \pi^+\pi^-$ ) hadronic decay channels. The two primary subsystems that we used in the analysis are the Time Projection Chamber (TPC) and the Time of Flight (TOF). TPC provides charged track reconstruction, momentum measurements and the particle identification via measurement of ionization losses,  $dE/dx$ . The momentum resolutions of the TPC is  $\delta p/p \sim 2\%$  and the energy resolution for  $dE/dx$  measurements is 6-8%. TOF subsystem has a time resolution of 60-100 ps depending on multiplicity.

To increase the reconstruction efficiency, we applied the following cuts. We selected events with the reconstructed primary vertex within 50 cm from the nominal interaction point. Reconstructed tracks were required to have at least 20 measured points in the TPC.

Possible edge effects in the TPC were suppressed by the pseudorapidity selection of  $|\eta| < 1.0$ . The reconstructed tracks were identified by using combined information about  $dE/dx$  in the TPC and time-of-flight in the TOF. Primary tracks were required to be matched to the primary vertex within two standard deviations in three projections. A set of topology cuts was used for reconstruction of  $K_s \rightarrow \pi^+ \pi^-$  decays in the secondary vertex to suppress combinatorial background.

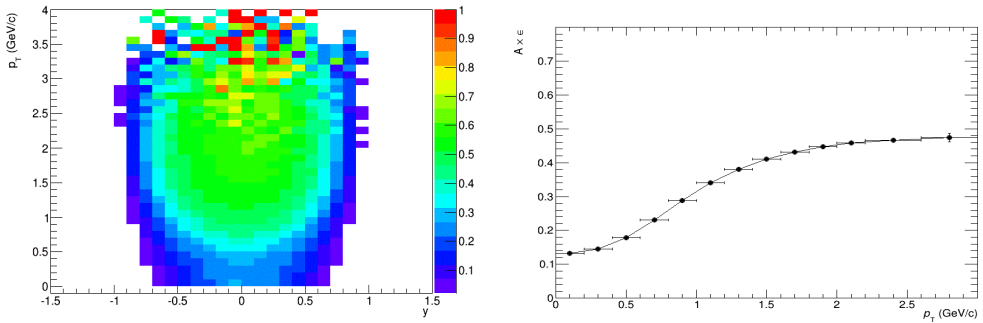
After reconstruction of the daughter particle candidates, the  $\pi K^\pm$  and  $\pi K^0$  invariant mass distributions were accumulated. The uncorrelated combinatorial background was estimated by using the mixed-event approach. In this approach, one of the daughter particles was taken from the same event and the second daughter particle was taken from a different event with similar topology by event vertex and multiplicity. Each event was mixed with 10 other events to reduce statistical uncertainties. The combinatorial background was scaled to the same event invariant mass distribution in the high mass region where correlations are not expected.

The examples of invariant mass distributions for  $\pi K^\pm$  (left) and  $\pi K^0$  (left) pairs are shown in Figure 4. The distributions are shown after subtraction of the scaled mixed event background. The invariant mass distributions are fitted with the sum of the second order polynomial and a Voigtian function. The second order polynomial describes the remaining correlated background. The Voigtian function is the convolution of the Breit-Wigner and Gaussian functions and is used to describe the signal. The widths ( $\Gamma$ ) of  $K^*$  resonances were fixed to the PDG values [4]. Statistical uncertainties for measurement of the charged  $K^*$  mesons are going to be larger compared to the case of neutral  $K^*$  mesons because of lower efficiency. Systematic uncertainties are yet to be determined. However,  $K_s$  mesons identification at high momentum can be more reliable than identification of the charged kaons.

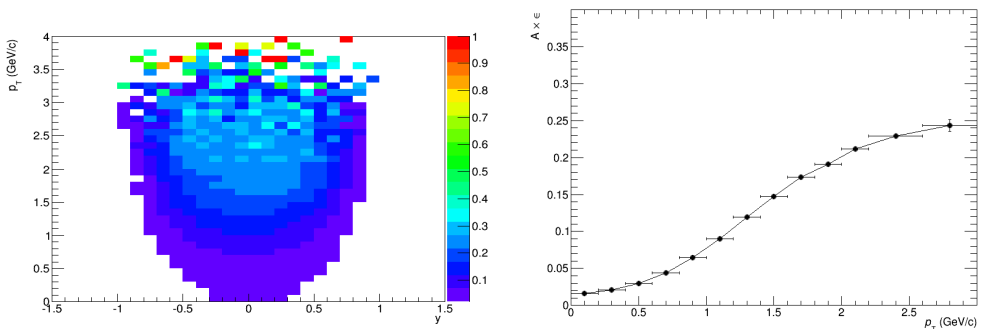


**Fig. 4.** The invariant mass distributions of  $\pi K^\pm$  (left) and  $\pi K^0$  (left) pairs in the  $p_T$  range 0.4-0.6 GeV/c. The distributions are fitted with the sum of the second order polynomial and a Voigtian function to account for the remaining correlated background and signal peaks.

The efficiencies for the reconstruction of neutral  $K^*$  mesons in the  $\pi K$  decay channel and charged  $K^*$  mesons in the  $\pi K^0$  decay channel as a function of particle momentum and rapidity are shown in Figure 5 and Figure 6, respectively. Efficiency increases with transverse momentum and saturates at higher momenta. The efficiency for reconstruction of the charged  $K^*$  resonances is smaller compared to the efficiency of neutral  $K^*$  resonances due to presence of the secondary vertex in the reconstruction chain.  $K^{*0}$  and  $K^{*\pm}$  resonances can be reconstructed in the rapidity range  $|\eta| < 1.0$  starting from zero momentum. The ability to measure  $K^*$  resonances at high  $p_T$  is limited by available statistics.

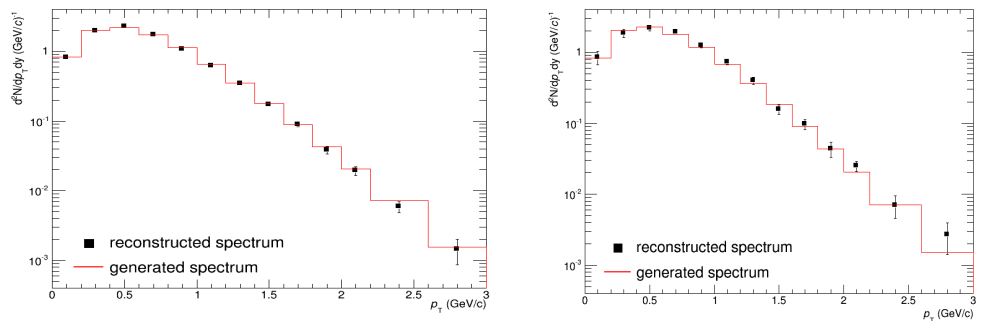


**Fig. 5.** The efficiency for the reconstruction of neutral  $K^*$  mesons in the  $\pi^\pm K^\pm$  decay channel as a function of particle momentum and rapidity (left) and  $p_T$  in the rapidity range  $|y| < 1.0$  (right).



**Fig. 6.** The efficiency for the reconstruction of charged  $K^*$  mesons in the  $\pi^\pm K_S$  decay channel as a function of particle momentum and rapidity (left) and  $p_T$  in the rapidity range  $|y| < 1.0$  (right).

To test the reconstruction chain, we performed the so-called Monte-Carlo closure test. The results of the closure tests for neutral  $K^*$  (left) and charged  $K^*$  (right) resonances are shown in Figure 7. The red histograms show the generated spectra and the black markers correspond to fully reconstructed  $p_T$ -spectra of  $K^*$  resonances. One can see that reconstructed spectra match the generated ones within uncertainties. It means that the developed reconstruction chain allows reconstruction of true generated signals in different  $p_T$ -intervals.



**Fig. 7.** The comparison of the reconstructed (black) with generated (red)  $p_T$  spectra of neutral  $K^*$  (left) and charged  $K^*$  (right) mesons.

The obtained results show that the reconstruction of  $K^*$  is going to be possible from zero momenta up to 3 GeV/c with an accumulated statistic of 10M events and for centrality-

dependent studies 100M events is required. With the expected luminosity of  $5 \cdot 10^{25} \text{ cm}^{-2}\text{s}^{-1}$  and 10 weeks of running with a duty factor of 50% one can expect  $\sim 10^9$  minimum bias Au+Au collisions at  $\sqrt{s_{NN}} = 11 \text{ GeV}$  sampled in the first year of running. This makes possible measurement of  $K^*$  resonance properties.

## 4 Conclusion

Model predictions show that  $K^*$  meson production will be sensitive to properties of the partonic/hadronic medium created in heavy-ion collisions at NICA energies. Thus, measurement and study of  $K^*$  production is an important part of the MPD physical program.

Feasibility studies showed that reconstruction of  $K^*$  mesons is going to be possible from zero momentum up to 3 GeV/c with an accumulated statistic of 10M events. The MPD detector will be able to collect sufficient statistics to measure the production of the  $K^*$  resonances in the first year of running.

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