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A METHOD OF η' DECAY PRODUCT SELECTION TO DETECT PARTIAL CHIRAL SYMMETRY RESTORATION

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In case of chiral $U_A(1)$ symmetry restoration the mass of the η' boson (the ninth, would-be Goldstone boson) is decreased, thus its production cross section is heavily enhanced [1]. The η' decays (through one of its decay channels) into five pions. These pions will not be correlated in terms of Bose–Einsten correlations, thus the production enhancement changes the strength of two-pion correlation functions at low momentum [2]. Preliminary results strongly support the mass decrease of the η' boson [3–5]. In this paper we propose a method to select pions coming from η' decays. We investigate the efficiency of the proposed kinematical cut in several collision systems and energies with several simulators. We prove that our method can be used in all investigated collision systems.

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1. CHIRAL SYMMETRY AND η' MASS

The temperature of the quark–gluon plasma created in gold–gold collisions of the Relativistic Heavy Ion Collider (RHIC) may reach values up to 300–600 MeV [6, 7]. At these very high temperatures the degrees of freedom are not hadrons but quarks or gluons. It is expected that the broken symmetries of QCD are partially restored in this matter. Originally, the $U_A(1)$ part of chiral symmetry is broken exactly, thus a high-mass meson is produced, the η' particle, which has a mass of 958 MeV. However, if the $U_A(1)$ symmetry is partially restored, the mass of the η' is decreasing [1].

Production cross sections of hadrons are exponentially suppressed by their mass. Hence, without mass modification roughly two orders of magnitute less η' mesons are produced than pions. In contrast, decreased-mass η' mesons will be created more abundantly. Thus, the number of η' mesons is closely related to their mass.

The decay of the η' happens after it regained its vacuum mass (at the expense of its momentum). One important decay channel is the decay into two leptons, $\eta' \to l^+ + l^-$; this is investigated in [8]. It turns out that there is an excess in the dilepton spectrum at low invariant mass, and this excess might be related to the η' enhancement. There is also a decay mode when the η' goes into an η and two pions, and the η also decays into three pions:

$$\eta' \to \eta + \pi^+ + \pi^- \to \left(\pi^+ + \pi^- + \pi^0\right) + \pi^+ + \pi^- \tag{1}$$

and the overall probability of this decay chain is 10% [9]. The average momentum of the resulting five pions is 138 MeV due to the low momentum of the original η' [2].

2. TWO-PION BOSE–EINSTEIN CORRELATIONS

Final state effects distort two-particle correlation functions. One of the most important final state effects is that of Bose–Einstein correlations. To calculate these correlation functions, let us utilize the core–halo model. In the core–halo model [10], the hadronic source is divided into two parts: a core and a halo. The core consists of the primordial particles and decay products of very short lifetime resonances, thus its size is very small, roughly 5 fm. The halo consists of decay products of long-lived resonances, such as η, η' or K_S^0. The halo hadrons are created very far from the core, so the halo size is much larger, at least 50 fm. When measuring correlation functions, however, due to finite momentum resolution of the detectors, very small momentum differences cannot be resolved; i.e., pairs with such similar momenta are regarded as one by the detectors. In the Fourier transformation, large sizes correspond to small momenta, thus the halo correlations are not seen in measurements. Hence the observable part of the correlation function is due to the core, but its strength is decreased by the core/halo ratio. In case of a plain-wave approximation, for an identical boson pair with momenta p_1 and p_2, the two-particle correlation function is (for detail see, e.g., [10])

$$C_2(q,K) = 1 + \lambda \frac{|\widetilde{S}_C(q,K)|^2}{|\widetilde{S}_C(q=0,K)|^2}, \tag{2}$$

where $q = p_1 - p_2$, $K = (p_1 + p_2)/2$ and $\widetilde{S_C}(q,p)$ is the Fourier transform of the core source function (or emission function of pions coming from the core) $S_C(x,K)$ (the Fourier transformation is in $x \to q$). The important parameter here is $\lambda = N_C/(N_C + N_H)$, where the number of particles in the core is N_C, the number of particles in the halo is N_H. The λ parameter thus depends on the ratio of the core to the halo. The halo pions come partly from η' decays, so more η' means larger halo, and smaller λ. Hence η' mass and λ value are connected. This was investigated in [3–5], and it was found that the λ parameter is indeed decreasing at the kinematical domain of η' decay pions. However, it is not experimentally proven that the η' decay pions are causing the decrease. In this paper we investigate a method to kinematically filter out pions from η' decays. If applied to the experimental sample, in case of an η' mass modification the λ decrese will vanish.

3. KINEMATICAL DOMAIN OF PIONS FROM η' DECAYS

Our method is based on the invariant mass of pions from the decay chain mentioned in Eq. (1). Let us investigate the invariant momentum of π^+, π^- pairs in the above decays. Using the mass-shell condition for pions, and utilizing momentum conservation in the decay, one gets an m_{inv} interval for the π^+, π^- pair coming from the η', for the second pion pair coming from the η, and for the whole quadruplet. Based on the simulations, we chose the 0.075–0.171 GeV^2/c^4 interval for pairs and the 0.43–0.69 GeV^2/c^4 interval for quadruplets. This yields an effective method of kinematical selection of η' decay pions, as detailed in the next section.

For a given π^+, we form all possible pion quadruplets $(\pi^+, \pi^-, \pi^+, \pi^-)$ from the same event, and check if any of these quadruplets fulfill our m_{inv} criteria. If there is at least one, we consider the original π^+ to be «found». The same can be done by starting from a given

π^+, π^- pair. In simulations, we can determine if the pair of the particle comes from an η' decay, so the efficiency of the selection method can be tested. Whether using the pair or the single particle method, we can form four different groups of them:

a) Comes from an η' and fulfills the $m_{\rm inv}$ criteria;

b) Comes from an η' and does not fulfill the $m_{\rm inv}$ criteria;

c) Does not come from an η' and fulfills the $m_{\rm inv}$ criteria;

d) Does not come from an η' and does not fulfill the $m_{\rm inv}$ criteria.

Let us call the number of pions (or pairs in the other method) in the four groups N_a, N_b, N_c and N_d, respectively. Then the efficiency of cutting η' decay products is $N_a/(N_a + N_b)$; loss of statistics, i.e., fraction of lost non-η' pions is $N_c/(N_c + N_d)$. Note that a «found» pair or particle that is not coming from an η' (i.e., a loss greater than zero) decreases our experimental sample. The goal of the present paper is to investigate the efficiency and loss connected to our method. A similar method was investigated in [11] for e^+e^- collisions. We test the method in $p+p$ and Au + Au collisions of several energies.

4. RESULTS

We used two simulations to test our method: Pythia [12] (proton–proton collisions, version 8.135) and Hijing [13] (proton–proton and gold–gold collisions, version 1.411). We also simulated the geometric acceptance of the detectors. In case of the 200 GeV RHIC energy,

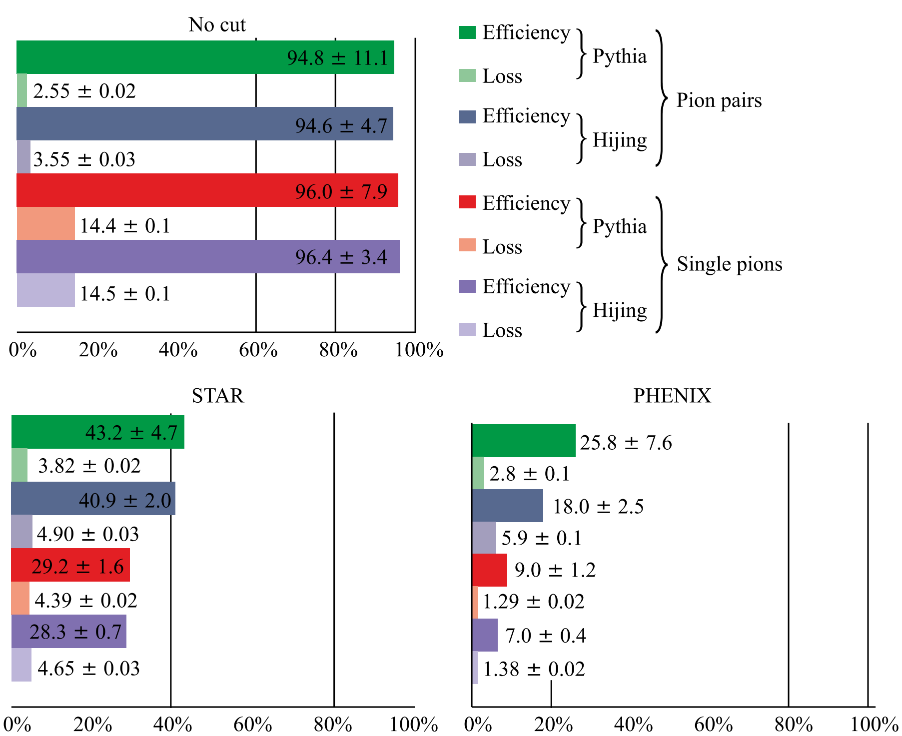

Fig. 1. Results from $\sqrt{s} = 200$ GeV $p+p$ collisions. The method is working in all cases, but the efficiency is very low in case of PHENIX cuts, for the single particle method

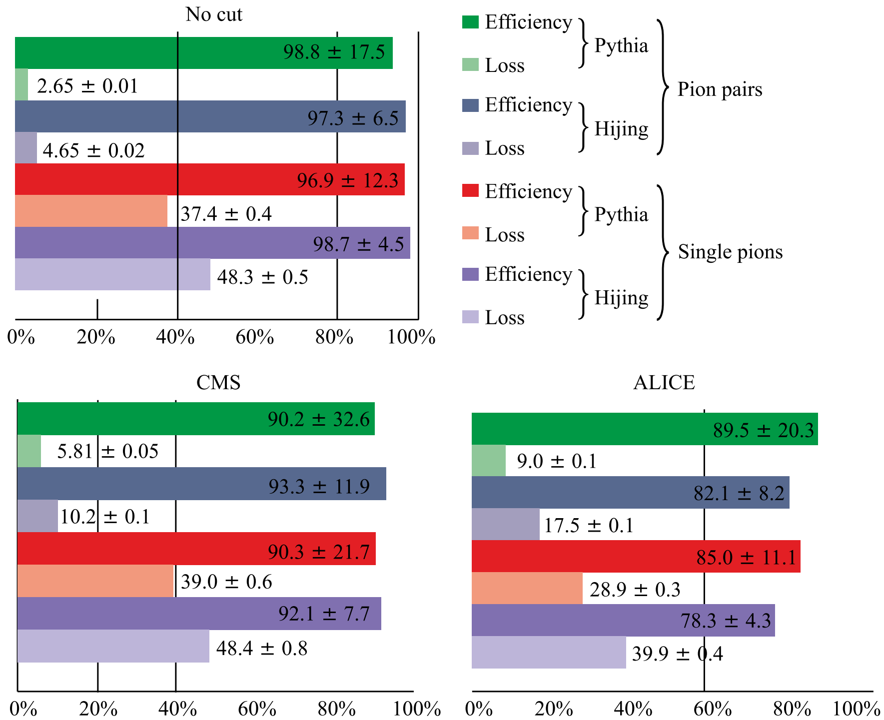

Fig. 2. Results from $\sqrt{s} = 200$ GeV $p + p$ collisions. The method is working in all cases

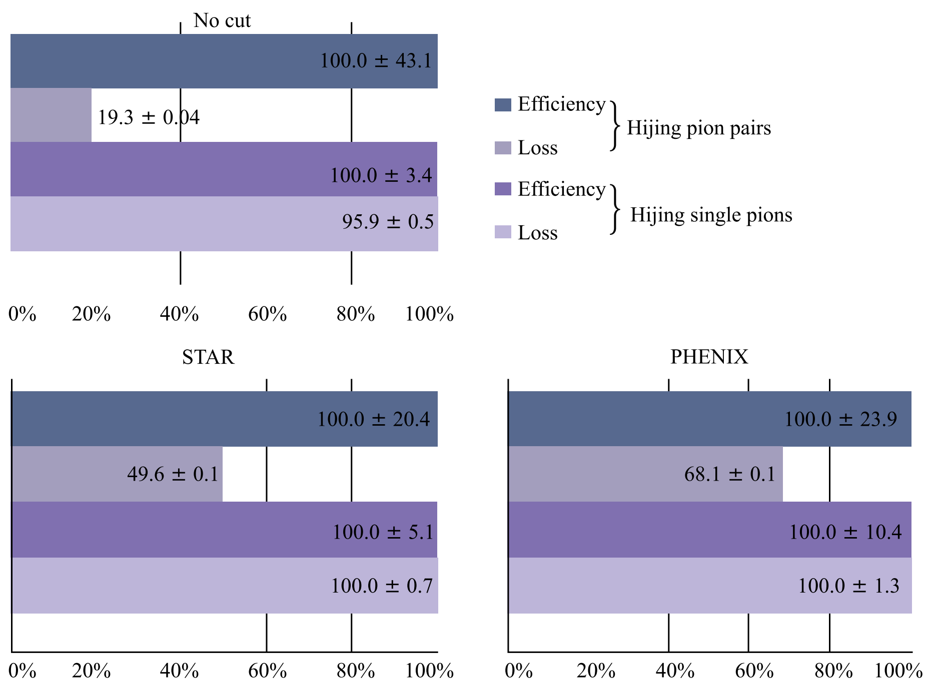

Fig. 3. Results from $\sqrt{s} = 200$ GeV Au + Au collisions. The method is working only in the pair method, as loss is 100% in the other case

we used the geometry of STAR and PHENIX detectors, while in case of 14 TeV energy, we used the geometry of ALICE and CMS detectors. We generated 1 000 000 $\sqrt{s} = 200$ GeV, 10 000 $\sqrt{s} = 14$ TeV $p + p$ events and 100 $\sqrt{s_{NN}} = 200$ GeV events. We calculated efficiency and loss of the method in all cases, see details in Figs. 1–3.

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