The possibilities of search for the local strong P-symmetry breaking in decay of charged a_0 meson in $3\pi^{\pm}$ decay channel

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In a hot and dense medium created in the collisions of heavy ions at high energy large topological fluctuations of QCD fields can occur, leading to possible effects of the local violation of P-symmetry in strong interactions. We proposed a search for charged a_0 meson decay into three charged pions as a signature of the local strong parity breaking. Using PYTHIA Monte Carlo generator with enabled required decay channels we investigated invariant mass spectrum and analyzed the signal and background contributions. As a result, we estimated minimal number of pp collision events for significant signal of the P-breaking decay.

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Introduction

Currently, there is no experimental evidences of the violation of the spatial parity (P) conservation in strong interactions. In the QCD theory, the P-breaking term (so-called θ-term) can be included into Lagrangian:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{\mu\nu,a}G^{a}_{\mu\nu} + \bar{q}(i\gamma^{\mu}D_{\mu} - \hat{m}_q)q, \tag{1}$$
$$D_{\mu} = \partial_{\mu} - iG^{a}_{\mu}\lambda^{a}, \quad G^{a}_{\mu\nu} = \partial_{\mu}G^{a}_{\nu} - \partial_{\nu}G^{a}_{\mu} + gf^{abc}G^{b}_{\mu}G^{c}_{\nu}$$

It can be supplemented by the θ-term that breaks the P symmetry:

$$\Delta\mathcal{L}_{\theta} = \theta\frac{g^2}{16\pi^2}Tr\left(G^{\mu\nu}\tilde{G}_{\mu\nu}\right) \tag{2}$$

with thight limits on the parameter value $\theta \lesssim 10^{-9}$.

However, in the medium with high temperature and at large topological fluctuations of QCD fields, expected in collisions of the heavy ions at high energy, the effects of the local violation of P-symmetry can appear.

One of the possible theories considers violation as a local breaking due to large topological fluctuations at high temperature and generation of configurations of nontrivial topological charge [1]. The contribution to the QCD Lagrangian of the topological charge can play role of an effective θ-term [2].

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Taking into account the partially conservation of the axial current, this term triggers phase with non-zero chiral chemical potential μ_5.

One of the most famous ways of searching the strong parity nonconservation effects is the chiral magnetic wave effect (CME) [3, 4] and chial magnetic wave (CMW) [5]. It can appear in the presence of the large magnetic field, which is characterized by semi-central and peripheral ion collisions. It was studied using charge-dependent angular correlations and flow at RHIC and LHC [6–9] and a CME-like signal was found. However, backgrounds contributions, like a local charge conservation, play a comparable role [10]. Nevertheless, the comparison of the experimental results with modelling [11] showed the best agreement is achieved for the μ_5 above 300 MeV.

The local parity violation effects, that can appear also in central heavy-collisions, involving the decays of light mesons with explicit parity non-conservation were considered in [12–15]. As it was shown using generalized sigma model with a background 4-vector of axial chemical potential, inside the medium with local parity breaking $a_0^{\pm}$ meson may be produced which decays by the channels that is forbidden by the parity conservation [15]. It was calculated [16] that for $\mu_5 = 500$ MeV and $|\vec{q}| = 128$ MeV such decay through electromagnetic mode ($a_0^{\pm} \to \pi^{\pm} + \gamma$) will occur with low branching ratio (BR) about 0.001%. As the expected electromagnetic cross section of this decay $a_0^{\pm} \to \pi^{\pm} + \gamma$ is rather low, it makes the experimental searches quite challenger even in Run 3 of the LHC data taking. Thus, we propose to search the parity forbidden decay of $a_0^{\pm}$ meson through strong interaction mode. From the comparison of the constants of strong interaction ($g^2 \sim 1$) and electromagnetic interaction ($\alpha_{\text{em}} \sim (1/137)$) it can be estimated that the BR of decay $a_0^{\pm} \to$ hadrons could be much large, of the order of 5–10%.

In this work we investigate the hadronc analogue of such process, namely, decay of a charged a_0 meson into three charged pions. Both direct three-particle decay and a resonance one, with intermediate ρ^0 meson ($a_0^{\pm} \to \rho^0 + \pi^{\pm} \to \pi^{\pm} + \pi^{\mp} + \pi^{\pm}$), can be considered. However, we focus on the mode with intermediate ρ_0 meson, as it can be used as a selection criterion. We study an invariant-mass spectrum of three charged mesons using PYTHIA Monte Carlo generator with enabled required decay channels. To distinguish the peak of mentioned decay from the background the mixed-event substracting, kinematic cuts and Dalitz plots analysis were used. As a result we have estimated minimal number of pp collision events for significant signal of the P-breaking decay.

The goal of our study is to check the possibility of experimental observation of the decay $a_0^{\pm} \to \rho^0 + \pi^{\pm} \to \pi^{\pm} + \pi^{\mp} + \pi^{\pm}$ using Monte Carlo simulations. Below in our simulations we will assume BR of this mode as 5%. This model can give a qualitative picture of experimental landscape while the calculation of exact BR value requires additional research.

1. Analysis of the generated data

We used PYTHIA8 Monte Carlo generator [17] (version 8.3) for pp collisions at $\sqrt{s} = 13$ TeV, with soft QCD processes under consideration and enabled $a_0^{\pm} \to \rho^0 + \pi^{\pm}$ decay channel ($BR = 5\%$). The invariant-mass ($M_{\pi\pi\pi}$) spectrum of final $\pi^{\pm} + \pi^{\mp} + \pi^{\pm}$ triplets, where $\pi^{\pm} + \pi^{\mp}$ pairs are produced by ρ^0, was under the analysis.

It is obvious that there are many decay chains ending in $3\pi^{\pm}$ final state besides the a_0 meson decay. Thus one should apply cinematic cuts for the pions under analysis. We used the following parameters for the particle selection:

- All π pairs in triplet must have invariant mass in the range of 0.278 GeV$< M_{2\pi} <$ 1 GeV.
- One $\pi^+\pi^-$ pair from triplet must have 0.625 GeV $< M_{2\pi} <$ 0.925 GeV which corresponds ρ^0 mass.
- All π pairs that have invariant mass in the range of 0.4 GeV$< M_{2\pi} <$ 0.6 GeV are rejected due to high fraction of σ meson decay.
- Distance of closest approach cut for the particle production coordinates: DCA $<$ 35 μm to suppress particles from weak decays. The selected threshold correspond to the capabilities of the ALICE experiment at LHC after the ITS upgrade.

It was found a large combinatorial background of $\pi^{\pm}$ triplets. To distinguish the correlated signal we used the event mixing technique. The resulting invariant mass spectrum of correlated pairs is shown at Fig. 1.

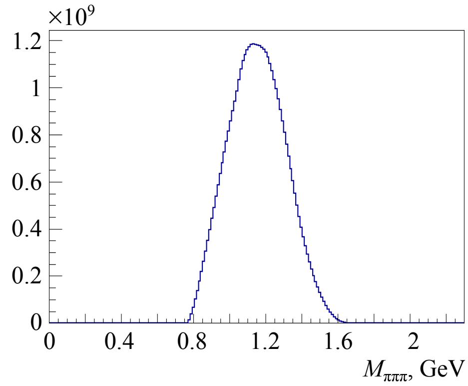

Fig. 1. Correlated invariant mass spectrum after mixed event substraction.

2. Composition of correlated signal

Let us discuss in detail what contributes to the correlated invariant mass spectrum. As far as we used Monte Carlo simulation, it is possible to accurately identify each particle and the process of its production. The Fig. 2, left, represents all significant contributions in invariant mass spectrum. It is clearly seen the dominance of the correlations attributed to diquarks. Such effect in PYTHIA model correspond to jet or mini-jet contributions. One can expect the smooth behaviour of diquarks spectrum in the range of $a_0^{\pm}$ mass. In that case and with the sufficient amount of statistics there would be possible to distinguish the signal $a_0^{\pm} \to 3\pi^{\pm}$ from the mini-jets background. In addition, the same-sign pair subtraction technique can be applied. As it was shown in the ρ_0 meson analysis [18], it reduces the both combinatorial and correlated hadronic background drastically.

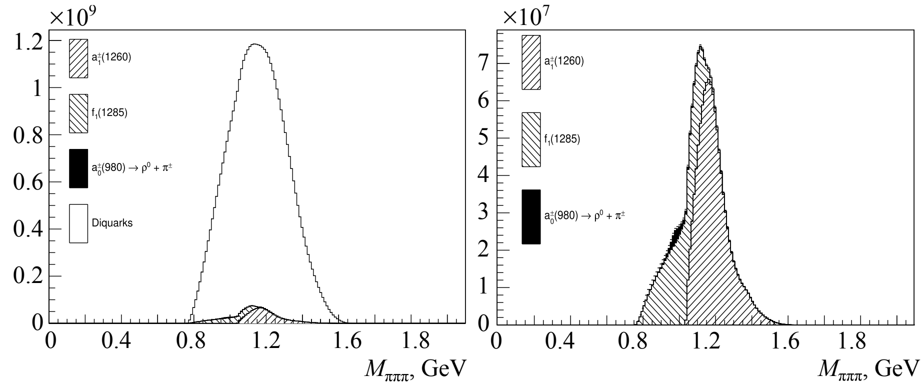

Fig. 2. The composition of correlated invariant-mass spectrum with diquarks (left) and without them (right). The most abundant contributions are shown.

The correlated spectrum without diquarks (Fig. 2, right) contains only contributions from well known [19] resonances decays. There are mostly three decay chains that influence the region of interest (Fig. 3).

1. The decay of axial vector meson $a_1^{\pm}(1260) \to \rho^0 + \pi^{\pm}$ is allowed by the parity conservation and undergoes with $BR = 35\%$. All products are correspond to the desired decay of $a_0^{\pm}$. With good enough experimental resolution it will be possible to identify each peak due to mass difference between $a_1^{\pm}(1260)$ and $a_0^{\pm}(980)$.

2. $a_0^{\pm}$ mostly (90%) decays to $\eta + \pi^{\pm}$. Then there is a 23% possibility for η to produce $\pi^- + \pi^0 + \pi^+$. Thus, this chain gives triplet of charged pions. Nevertheless neutral pion produced in this mode takes away energy-momentum part of the $a_0^{\pm}$ mother so the peak moves left from its original mass.

3. $f_1(1285)$ meson undergoes several decays that produce four charged pions in the final state:

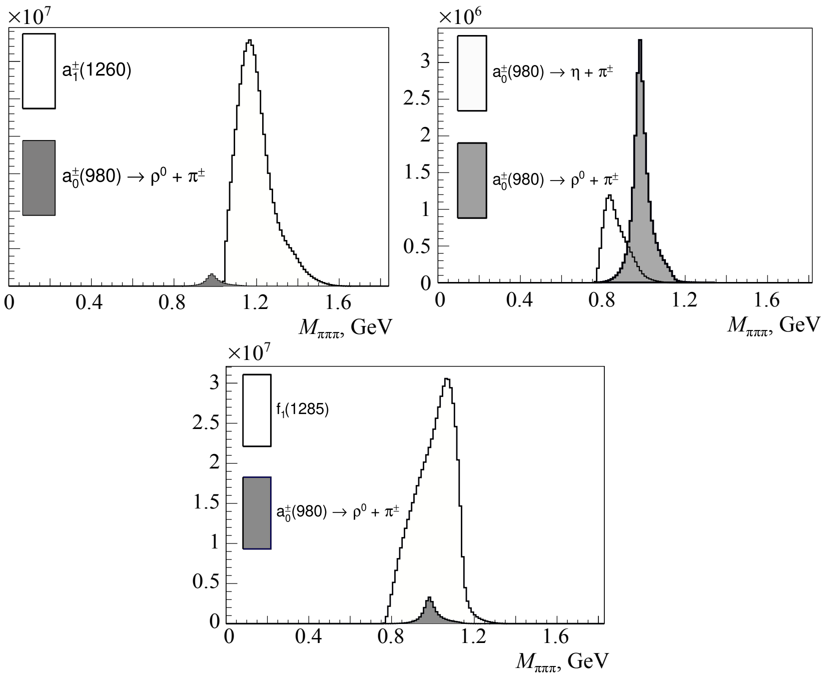

Fig. 3. The comparision of invariant mass spectrum from $a_0^{\pm} \to 3\pi^{\pm}$ decay compared with that from decay of $a_1^{\pm}(1260)$ (left), standard $a_0^{\pm}$ decay through η (right) and $f_1(1285)$ decay (bottom).

$$f_1 \to a_0^{\pm}(980) + \pi^{\pm}(BR = 24\%)$$
$$f_1 \to \rho^0 + \pi^+ + \pi^-(BR = 11\%)$$
$$f_1 \to \eta + \pi^+ + \pi^-(BR = 14\%)$$

We note that 4-particle decay kinematics spreads widely mass of $f_1(1285)$ over 3-particle invariant mass spectrum. As a result, $a_0^{\pm}$ peak is fully overlapped by f_1.

3. Discussion

Using the calculation of the invariant mass spectrum in the Pythia Monte Carlo generator we obtained the yields of the discussed $a_0^{\pm} \to \pi^{\pm} + \pi^{\mp} + \pi^{\pm}$ decay, as well as background contributions. We can estimate the confidence level of our decay using $CL = \dfrac{S}{\sqrt{S+B}}$, were S is the signal yield of $a_0^{\pm} \to 3\pi^{\pm}$ decays and B is the full correlated background. The condition $CL = 5$ corresponds to $n_{\rm ev} \approx 140$ mln. events of pp collisions. In the ideal case that number of events is enough for 5σ discovery potential of parity breaking.

However, there are some issues that complicates picture. Firstly, the behavior of correlated background (mostly from minijets) can be irregular and thus hard to cut off. The interaction of minjets with medium also can modify the background behaiour. Moreover, the presence of $f_1(1285)$ 4-particle decay contribution in invariant mass spectrum has to be accurately assessed and properly subtracted. Finally, in the real experiment the following issues may show up: incomplete registration efficiency, inaccurate π identification, imperfect momentum and DCA resolution, etc.

On the other hand, additional measures for the significance enhancement and the background suppression can be considered. The detailed Dalitz plot analysis should be performed, taking into account the topological cuts and angular constraints. The joint template fits of all light flavour resonances can be applied to extract signal yields. Finally, a machine learning (ML) based approach [20] for candidate selection can be developed and applied.

Overall, our calculations show that the search of local P-parity in the strong interactions seems feasible given the event statistics, available at the LHC both in pp and heavy ion collisions.

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