PROCEEDINGS OF SCIENCE

NEW PHYSICS AT NICA

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The Nuclotron-based Ion Collider fAcility (NICA), situated in Dubna, Russia, is a circular accelerator complex designed for the acceleration of particles ranging from light protons to heavy ions such as Au and Pb. While NICA's primary focus lies in the exploration of nucleon structure and quark-gluon plasma, its capabilities extend to probing fundamental new physics. In this presentation, we elucidate the promising potential of NICA in uncovering new physics (NP), employing models featuring Dark Photons (DP) and Axion-Like Particles (ALP) as illustrative examples.

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1. Introduction

NICA will feature two collision points, each equipped with specialized detectors: the Multi-Purpose Detector (MPD) [1] and the Spin Physics Detector (SPD) [2]. This study primarily focuses on the capabilities of the MPD. Expected collision energy at NICA is set to 10 GeV per nucleon, with an expected luminosity of up to 10^{27} cm^{-2} s^{-1}, resulting in the production of approximately 10^{13} pions in 10 weeks [3].

The collision energies achieved at NICA indicate that the most promising mass range for new physics (NP) particles is sub-GeV. Within this context, we explore models with Dark Photons (DP) and Axion-Like Particles (ALP). Our study identifies the most promising sources of NP particles, examines their decay signatures, and estimates NICA's sensitivity to model parameters.

2. Models

The first model under discussion is a hypothetical light vector particle A' [4] . It couples to SM through kinetic mixing with photon, represented by the Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon'}{2}F'^{\mu\nu}F_{Y\mu\nu}. \tag{1}$$

After field redefinition, mixing in Lagrangian (1) yields the interaction of A' with SM currents

$$\mathcal{L}_{DP} = \epsilon e A'^{\mu} j_{\mu}. \tag{2}$$

The second model is Axion-Like Particle with coupling to SM photons, described by the Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{m_a^2}{2}a^2 - \frac{g_{\gamma\gamma}}{4}F^{\mu\nu}\tilde{F}_{\mu\nu}. \tag{3}$$

While other couplings to fermions and bosons are possible, we do not consider them here due to their small branchings compared to photons. However, in specific models, decays of ALP and DP to the hidden sector might occur, providing a sizable contribution to branchings and lifetime. To account for these possible decays, we introduce the Half Hidden (HH) case, where we take the total width of NP particle as $\Gamma_{tot} = 2\Gamma_{SM}$ and HH/5, where $\Gamma_{tot} = 10\Gamma_{SM}$. The first case corresponds to models where the couplings to the hidden sector are of the same order as the couplings to SM, while the second case corresponds to models where the hidden sector decays dominate.

3. Displaced Vertex Signature

Both DP and ALP can travel macroscopic distances before decaying into visible particles. Given this, we propose searching for a displaced vertex signature. A crucial feature of the NICA MPD is its Initial Tracking System (ITS), scheduled for installation after an upgrade [5]. This system allows the determination of secondary vertex positions with a precision of up to ~ 10 μm, significantly reducing the background to a negligible level. To compare different scenarios with the ITS, we conducted calculations for various minimal travel distances of NP particles: $L_{min} = 10$ μm,

L_{min} = 100 μm and L_{min} = 1000 μm. The probability of a particle to travel a distance larger than L_{min} is given by

$$P = \exp\left(-\frac{L_{min}}{d}\right) - \exp\left(-\frac{L_{max}}{d}\right), \tag{4}$$

where $L_{max} \sim$ 1m is the detector size and $d = \tau\gamma\beta$ is the mean travel distance. In our case $L_{max} \gg d$ simplifying the probability to

$$P = \exp\left(-\frac{L_{min}}{d}\right). \tag{5}$$

Therefore, the number of signal events read:

$$N_S = N_{A'} \times P \times \frac{\Gamma(A' \to e^+e^-)}{\Gamma_{tot}}, \tag{6}$$

$$N_S = N_a \times P \times \frac{\Gamma(a \to \gamma\gamma)}{\Gamma_{tot}}, \tag{7}$$

where $N_{A'}$ and N_a are the numbers of produced hidden vectors A' and ALPs a.

4. Dark Photon

Interaction of A' with the SM, as presented in (2) introduces an additional decay channel of hadrons, which now can subsequently decay into SM photon and A'. Pseudoscalar mesons such as π and η are abundantly produced in heavy ion collisions at NICA, and they can decay into a pair of SM photons. Through kinetic mixing, one of these photons could be A'. The branching fractions for such decays are given by [6]

$$\mathrm{Br}\,(P \to \gamma A') = 2\epsilon^2\,\mathrm{Br}\,(P \to \gamma\gamma) \times \left(1 - \frac{m_{A'}^2}{m_P^2}\right)^3 \tag{8}$$

The produced hidden vector A' can potentially decay into SM particles, including lepton and meson pairs, with decay rates [7]

$$\Gamma\left(A' \to l^+l^-\right) = \frac{\epsilon^2 e^2}{12\pi} m_{A'} \left(1 + \frac{2m_l^2}{m_{A'}^2}\right)\sqrt{1 - \frac{4m_l^2}{m_{A'}^2}}, \tag{9}$$

$$\Gamma\left(A' \to hadrons\right) = \Gamma\left(A' \to \mu^+\mu^-\right) \times R(m_{A'}), \tag{10}$$

where $R(\sqrt{s}) = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$ is the energy dependent R-ratio [8].

To correctly calculate d of A' we account for the initial meson momentum. The momentum distribution of A' is obtained by boosting the momentum in the parent meson center-of-mass frame. The distributions by transverse momentum p_T and rapidity y for initial mesons are obtained in simulations of BiBi collisions at $\sqrt{s_{NN}}$ = 9.2 GeV performed with PHSD generator [9]. We integrate these distributions to obtain normalized to unity dn_X/dp_X distribution over meson 3-momentum. Then we transform Eq.(6) accordingly and get

$$N_S = \int dp_X\, N_X \frac{dn_X}{dp_X} \times \mathrm{Br}\,(X \to A') \times \mathrm{Br}\,(A' \to SM) \times P. \tag{11}$$

Here N_X - number of produced pseudoscalar mesons, $d \equiv 1/\Gamma_{tot} \times p_{A'}/m_{A'}$ and $p_{A'}$ is the A' 3-momentum in the laboratory frame. Since MPD can only detect photons with energies exceeding 50 MeV, we accordingly constrain the momenta in the integral (11).

Within this approach we arrive at the results depicted in Figs.1, 2, where black lines correspond to 3 signal events (lepton pairs) consistent with limits at 95% CL in the background free case. Results show that new regions of models parameter space can be explored at NICA after 10 weeks of operation.

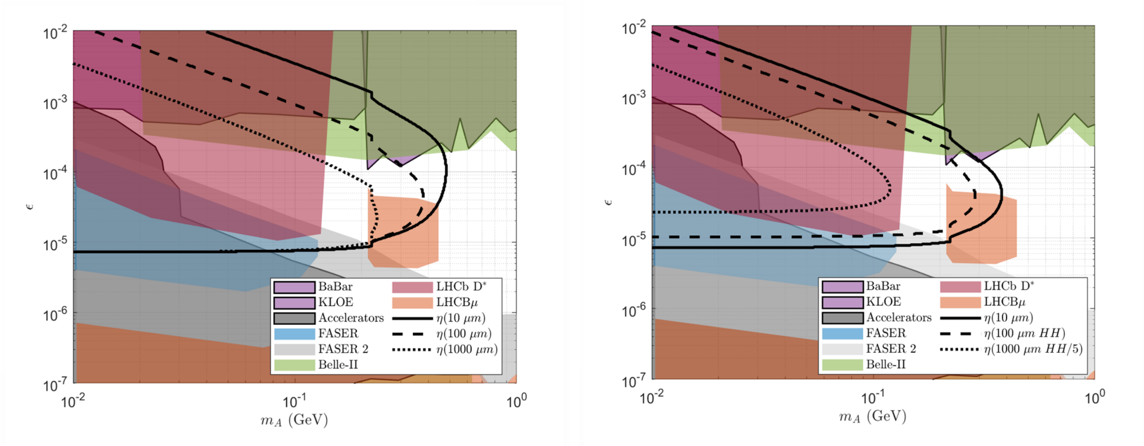

Figure 1: The regions to be probed at NICA after 10 weeks of operation at 95% CL with A' produced in η meson decays. Left plot shows results for different minimal recognizable travel distance of A', parameterized by L_{min} in eq. (5). Right plot shows results for different values of Γ_{tot}. The existing limits (colored and outlined) are taken from BaBar at 90% CL [10], KLOE at 90% CL [11], accelerator experiments (NA64 at 90% CL [12], E141 at 95% CL [13], NuCal at 95% CL [14]) and expected reaches of the ongoing experiments (colored) are given for FASER at 95% CL [15], Belle-II at 90% CL [16], LHCb D* at 95% CL [17], LHCBμ at 95% CL [18].

5. Axion-Like particle

The second model involving ALPs is described by Lagrangian (3). Along with the effective coupling of pseudoscalar mesons to photons [19]

$$\mathcal{L} = \frac{\alpha}{4\pi f} c_P \; P \, F_{\mu\nu} F_{\lambda\rho} \epsilon^{\mu\nu\lambda\rho}, \tag{12}$$

where $f = 92.4$ MeV, $c_\pi = 1,\ c_\eta = 1.10,\ c_{\eta'} = 1.34$, this model yields decays of mesons to axions $P \to \gamma\gamma a$ through the diagram depicted in Fig.3.

The width of ALP decay to photons is

$$\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}. \tag{13}$$

In our analysis, calculating ALP production and ALP decays we account for only coupling to photons. Generically, there could also be ALP interactions with leptons and quarks. Couplings to

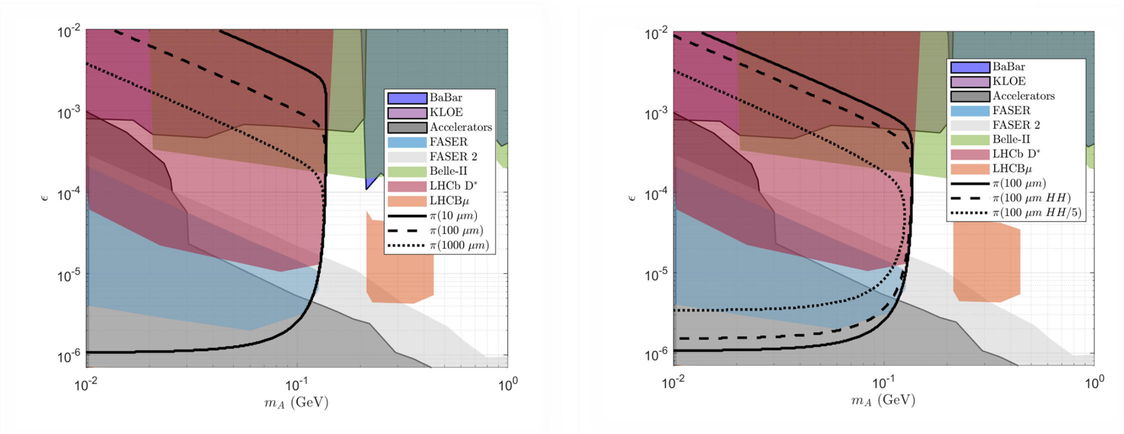

Figure 2: The regions to be probed at NICA after 10 weeks of operation at 95% CL with A' produced in π^0 meson decays. Left plot shows results for different minimal recognizable travel distance of A', parameterized by L_{min} in eq. (5). Right plot shows results for different values of Γ_{tot}. The existing limits (colored and outlined) are taken from BaBar at 90% CL [10], KLOE at 90% CL [11], accelerator experiments (NA64 at 90% CL [12], E141 at 95% CL [13], NuCal at 95% CL [14]) and expected reaches of the ongoing experiments (colored) are given for FASER at 95% CL [15], Belle-II at 90% CL [16], LHCb D* at 95% CL [17], LHCBμ at 95% CL [18].

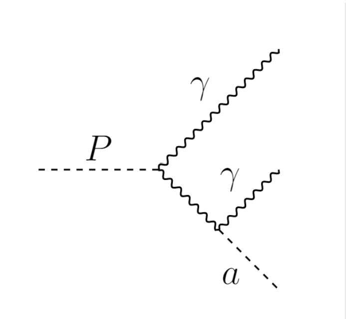

Figure 3: The Feynman diagram for the production of axion in pseudoscalar radiative decays.

fermions open new decays to pairs of electrons, muons and mesons. Typically, ALP decay rates to pair of leptons are suppressed by m_l^2/m_a^2 [20]. Nevertheless, even though we somewhat account for them by introducing HH and HH/5 cases with an additional to photon contribution to the ALP total width, coupling to fermions could provide another source of ALPs, such as weak decays of K-mesons [21, 22]. In our case, where the photon coupling dominates, we neglect all other possible additional sources of ALP production, and consider only the two-photon displaced vertex as the signature of ALP decay inside the NICA MPD detector. This implies that, together with HH and HH/5 cases we obtain conservative estimates of the NICA reach.

For ALPs we use the same simulations of ion collisions as we exploited above for the model with A'. The squared amplitude of process depicted in Fig.3 is calculated using CalcHEP package [23] and then integrated over the interesting region of the phase space as explained in the case of A'. The achieved results are depicted in Fig.4, where the black line refers to 3 signal events required within the Poisson statistics to exclude the corresponding outlined regions at 95% CL.

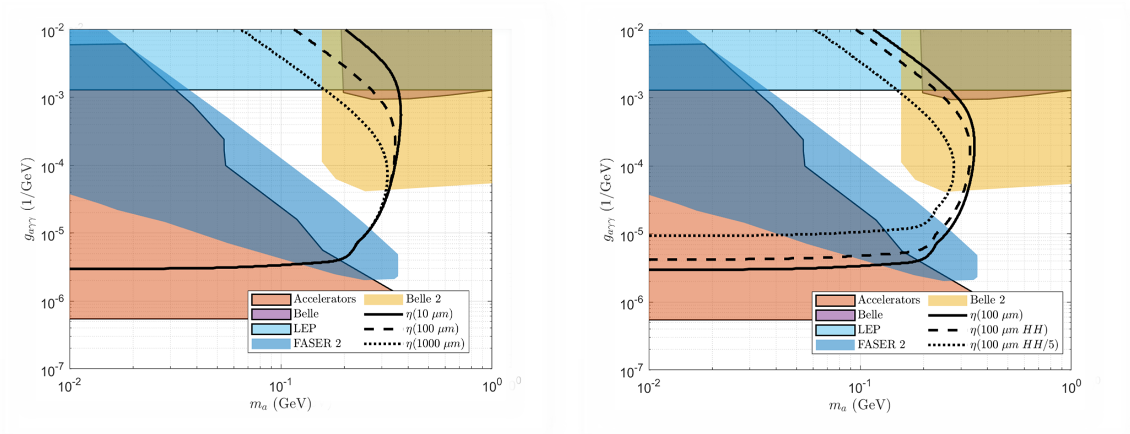

Figure 4: The regions to be probed at NICA after 10 weeks of operation at 95% CL with ALPs produced in η meson decays. Left plot shows results for different minimal recognizable travel distance of ALP, parameterized by L_{min} in eq. (5). Right plot shows results for different values of Γ_{tot}. The existing limits (colored and outlined) are taken from Belle at 95% CL [24], LEP at 95% CL [25], accelerator experiments (NA64 at 90% CL [26], E137 at 95% CL [27], NuCal at 90% CL [28]) and expected reaches of the ongoing experiments (colored) are given for FASER at 95% CL [29], Belle-II at 90% CL [30].

We find that the pion contribution to the ALP production is negligible for the model parameters in the previously unexplored regions.

6. Summary

To summarize, in this letter, we initiate an exploration of NICA's potential in searches for hypothetical light particles. We investigate models involving light vectors and axion-like particles. Following the upgrade of MPD with ITS, the displaced vertex becomes a viable signature for the decays of these light particles. This capability enables the exploration of previously uncharted regions within the parameter space of new physics models, providing a cross-check with results from other ongoing experiments. By incorporating the HH case into our analysis, we broaden the spectrum of models that NICA can effectively explore. Promising prospects may also exist for NICA in testing models with light scalars and axial vectors.

Our collaborative discussions with V. Riabov have highlighted challenges in achieving the background-free condition due to detector imperfections. Namely the misinterpretation of pions from kaon decays as electrons. This necessitates accounting for the detector's reconstruction efficiency in our calculations. To do so we focus on events with only pure electrons. With detector efficiency of 40% we require to collect not 3 but 3/0.16=18 signal events. This adjustment correspondingly reduce sensitivity regions in Figs.1 and 2 by a factor of ≈ 2.5. To compensate this we consider longer period of data taking, not 10 weeks but 1 year. The results and details of this approach are presented in [31]. This extended period of time will include several accelerator runs with different colliding ions. To consider this correctly one needs to know the accelerator operating schedule, including the specifics of colliding ions and luminosity, among other factors. Additionally, to accurately estimate potential background coming from miscellaneous sources, such as random scatterings or inaccurate event reconstruction, it is essential to conduct detailed simulations of the physics within detector systems. This, however, depends on the finalization of technical details, which are currently under discussion. Also our results for ALPs will may benefit from considering fermionic couplings and non-radiative decays of mesons to ALPs inherent in particular models, we do not anticipate a significant improvement in NICA's sensitivity. Despite these challenges, our initial findings prove that NICA's potential in searches for new physics is indeed promising and merits further exploration.

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