Search for new physics in ρ^0 meson decays in the NA64 experiment

Поиск новой физики в распадах ρ^0 мезона в эксперименте NA64

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Установка NA64 является универсальным детектором для проверки большого количества моделей за пределами Стандартной модели. Часть таких моделей предполагает образование частиц лёгкой тёмной материи, наличие которых можно определить по косвенным признакам. Поиски таких частиц, в частности тёмного фотона A' (векторного медиатора между обычной и тёмной материей), ведутся в эксперименте NA64. В статье рассматривается моделирование одного из каналов образования тёмного фотона через распад ρ^0 мезона на частицы тёмной материи.

The NA64 experimental setup is a universal detector designed to test a wide range of models beyond the Standard Model. Some of these models predict the existence of light dark matter particles, whose presence can be inferred from indirect evidence. The NA64 experiment is searching for such particles, specifically the dark photon A' – a vector mediator between ordinary and dark matter. This paper focuses on simulating a specific dark photon production channel: the decay of a ρ^0 meson into a dark photon, which subsequently decays into dark matter particles.

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Introduction

Along with the direct search for dark matter (DM) particles, the search for indirect evidence of DM's existence is also popular. The NA64 experiment [1] is based on this method. The main goal of the experiment is to search for light dark matter (LDM) with a mass ($m_\chi \leq 1\ GeV$). LDM particles can be the lightest stable states of a new Dark Sector (DS), with its own particles and fields [2–4]. In these models, a light vector boson A' mediates between Standard Model (SM) matter and the DS.

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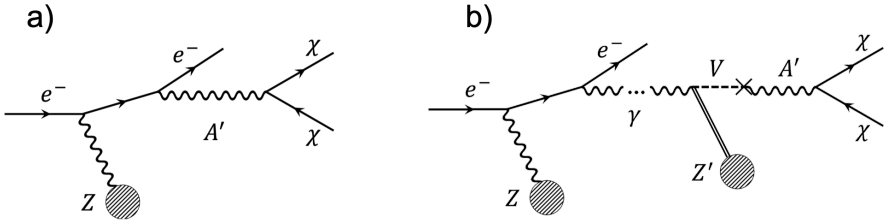


Fig. 1. a) Schematic view of the dark photon A' in a Bremsstrahlung process. b) Schematic view of the vector meson (where $V = \rho, \omega, \varphi$) production in an exclusive photoproduction process in the target (ECAL). The vector meson then decays invisibly to DM via mixing with the dark photon A'.

There are several production mechanisms for A' particles [5]. For searches of invisible dark photon decay modes, where the A' is reconstructed as missing mass, the bremsstrahlung process $e^-Z \to e^-ZA'$ and the annihilation channel $e^+e^- \to \gamma A'$ are favored. Low-mass dark photons can be produced via meson decays such as $\pi^0/\eta/\eta' \to \gamma A'$. Furthermore, in hadron colliders and proton fixed-target experiments, it is also feasible to study the Drell–Yan process $q\bar{q} \to A' \to l^+l^-$ (h^+h^-). The most studied mechanism of the production of dark photon is Bremsstrahlung process (see Fig. 1). Depending on the model and mass hierarchy, A' decays into LDM particles ($m_{A'} > 2m_\chi$), which leave the detector, or into SM particles ($m_{A'} < 2m_\chi$). In the first scenario, a significant portion of the initial energy is lost as the dark-matter particles escape undetected. In contrast, in cases where the mediator is sufficiently long-lived and decays visibly prior to dark-matter production, the vertex signatures will be shifted.

ρ^0 meson search strategy

Decays of the vector neutral mesons, such as ρ, ω, φ, provide a unique opportunity to test new physics beyond the Standard Model (SM) [6]. This transformation occurs in exclusive photoproduction processes via the Glauber mechanism (see Fig. 2) with energy loss. The NA64 facility is sensitive to processes in which beam energy is transferred to DM particles, resulting in a missing energy signal. Invisible decays of the light mesons ω and φ have been investigated at the BES III experiment [7], while for ρ^0 there are no experimental limits. Obtaining an experimental result is still a pressing task.

The strategy of searching for ρ^0 invisible decay [8] is similar to searching for A' in the NA64. The target of the setup is an electromagnetic calorimeter (ECAL). A hard photon is produced in the ECAL, and converts to a vector meson V in an exclusive photoproduction process in the ECAL. The vector meson then decays invisibly to DM via mixing with the A'. The typical signature for the LDM detection is missing energy in the ECAL without essential activity in the hadronic calorimeter (HCAL). For the investigation of ρ^0 invisible decays the same signature will be used.

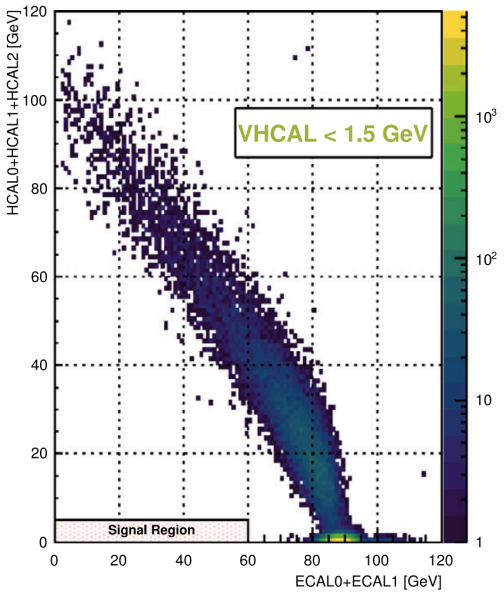


Fig. 2. Distribution of events in the (E_{ECAL};E_{HCAL}) plane after applying all selection criteria. The shaded area is the signal box.

To search for the desired DM event, the energies deposited in ECAL and HCAL are compared. For SM events, the sum of the deposited energy in ECAL and HCAL should be equal to the electron beam energy $E_{ECAL} + E_{HCAL} \simeq 100$ GeV. The missing energy carried away by the dark photon equals $E_{miss} = E_{A'} = E_e - E_{ECAL}$. The optimal boundary of the signal box for the ECAL was $E_{ECAL} = 47 - 50$ GeV for the 2016-2022 runs. [9]. To further improve sensitivity, as part of the upgrades to the setup, a prototype veto hadron calorimeter (VHCAL) was installed during the 2023 run [10]. The plot (see Fig. 2) demonstrates the role of this calorimeter, since the VHCAL total energy cut increases the signal region to 60 or even 70 GeV. In the case of the ρ^0 meson that decays into DM particles, its energy as well as $E_{A'}$ is a fraction of E_e and is equal to $E_{\rho^0} = E_e - E_{ECAL}$. Taking into account the boundary of the signal box, the energy of the ρ^0 should be $E_{\rho^0} > 40$ GeV or $E_{\rho^0} > 30$ GeV optimistically.

Simulation of the ρ^0 meson production at NA64

The simulation was performed using the Geant4 package [11]. Based on the results of the simulation of 10^8 events, about 12.8×10^3 ρ^0 mesons were produced. The calculated results based on the simulation are shown in Table 1. These calculations are based on the current NA64 statistics, preliminary statistics for 2026, and future statistics to be collected during RUN 4. Constraints on the decays of invisible ρ^0 mesons are represented in fig. 3.

The simulation results differ from the theoretical calculations given here [6] by 1 order of magnitude. Note that Geant4's hadronic models do not in-

Statistics	N_{EOT}	$E_{\rho^0} = 40$ GeV	$E_{\rho^0} = 30$ GeV
Current	2.6×10^{12}	2.6×10^{6}	2.7×10^{6}
Current + 2026	3.4×10^{12}	1.23×10^{7}	2.96×10^{7}
Ultimate (+ RUN 4)	10^{13}	3.64×10^{8}	8.74×10^{8}

Table 1. Expected number of ρ^0 mesons for current and future statistics.

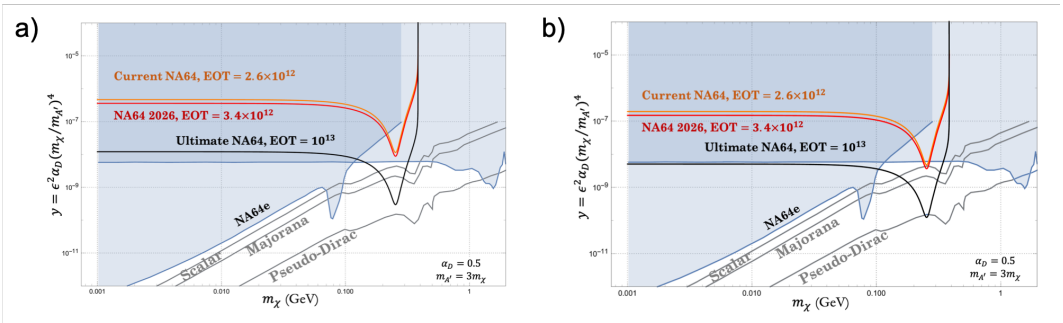


Fig. 3. Constraints on the decays of invisible ρ^0 mesons calculated for a) $E_{\rho^0} > 40$ GeV and b) $E_{\rho^0} > 30$ GeV. The filled area represents the existing experimental bounds for the dark photon models.

clude detailed simulations of exclusive photoproduction processes. In other words, Geant4 describes the process of incoherent photoproduction, but for a full assessment of the yield of ρ^0 mesons in the experiment, it is also necessary to take into account the process of coherent photoproduction on nuclei. In fact, it is impossible to provide a complete simulation of the process using Geant4 alone. Additional generators are capable of handling this task. For example, the generator eSTARlight [12] was developed for coherent exclusive photo- and electroproduction of vector mesons at the future Electron-Ion Collider (EIC). It is planned to adapt the generator to a fixed target experiment.

Conclusion

Adding data from the coherent photoproduction generator will yield a result increasing the number of ρ^0 mesons by an order of magnitude. This will also increase the peak size, which appears inconclusive for incoherent processes. A coherent process will be added to the simulation. The full implementation of the search for the invisible ρ^0 decay will continue.

REFERENCES

1. *Andreas S. et al.* [The NA64 Collaboration] Proposal for an Experiment to Search for Light Dark Matter at the SPS // — 2013. — arXiV:1312.3309

2. *Arkani-Hamed N., Finkbeiner D. P., Slatyer T. R., Weiner N.* A theory of dark matter // Phys. Rev. D — 2009. — V. 79. — P. 015014.

3. *Strassler M.J., Zurek K. M.* Echoes of a hidden valley at hadron colliders // Phys. Lett. B — 2007 — V. 651 — P. 374–379 —

4. *Andreas S., Goodsell M. D., Ringwald A* Dark matter and dark forces from a supersymmetric hidden sector // Phys. Rev. D — 2013 — V. 87 — P. 025007 —

5. *Alexander J. et al.* [Dark Sector Collaboration] Dark Sectors 2016 Workshop: Community Report // — 2016. — arXiv:1608.08632

6. *Schuster P., Toro N., Zhou K.* Probing invisible vector meson decays with the NA64 and LDMX experiments // Phys. Rev. D — 2022 — V. 105 — P. 035036 — arXiv:2112.02104

7. *Ablikim M. et al.* [BESIII Collaboration] Search for invisible decays of ω and ϕ with J/ψ data at BESIII // Phys. Rev. D — 2018 — V. 98 — P. 032001 — arXiv:1805.05613

8. *Gertsenberger S. V., Ivanov A. V., Zhevlakov A. S.* Production of ρ^0 Meson in the Target of the NA64 Experiment // Phys. Part. Nuclei Lett. — 2025 — V. 22 — P. 1129–1131

9. *Andreev Yu. et al.* [NA64 Collaboration] Search for Light Dark Matter with NA64 at CERN // Phys. Rev. Lett. — 2023 — V. 131 — P. 161801

10. *Andreev Yu. et al.* [NA64 Collaboration] High efficiency veto hadron calorimeter in the NA64 experiment at CERN // Nucl. Instrum. Methods Phys. Res. A — 2026 — V. 1081 — P. 170830

11. *Agostinelli S. et al.* [Geant4 Collaboration] Geant4—a simulation toolkit // Nucl. Instrum. Meth. A — 2003 — V. 506 — P. 250–303

12. *Lomnitz M., Klein S.* Exclusive vector meson production at an electron-ion collider // Phys. Rev. C — 2019 — V. 99 — P. 015203