Search for the dark photon in π^0 decays

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Abstract. A sample of 1.69×10^7 fully reconstructed $\pi^0 \rightarrow \gamma e^+ e^-$ in the kinematic range $m_{ee} > 10 \text{ MeV}/c^2$ with a negligible background contamination collected by the NA48/2 experiment at CERN in 2003-04 is analysed to search for the dark photon (A') via the decay chain $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+ e^-$. No signal is observed, and preliminary exclusion limits on space of dark photon mass $m_{A'}$ and mixing parameter ϵ^2 are reported.

1 Introduction

High intensity kaon experiments provide opportunities for precision studies of π^0 decay physics due to the fact that kaons represent a source of tagged neutral pion decays, mainly via their $K^\pm \rightarrow \pi^\pm \pi^0$, $K^\pm \rightarrow e^\pm \pi^0 \nu$ and $K^\pm \rightarrow \mu^\pm \pi^0 \nu$ decays. One of them is the NA48/2 experiment at the CERN SPS, which collected a large sample of charged kaon ($K^\pm$) decays in flight in 2003–04 corresponding to $\sim 2 \times 10^{11}$ $K^\pm$ decays in the fiducial decay volume [1].

This large sample of π^0 mesons produced and decaying in vacuum collected by NA48/2 allows for a high sensitivity search for the dark photon (A'), a hypothetical gauge boson appearing in hidden sector new physics models with an extra U(1) gauge symmetry. In these models the interaction of the dark photon with the visible sector proceed through kinetic mixing with the Standard Model (SM) hypercharge [2]. Such scenarios with GeV-scale dark matter provide possible explanations to the observed rise in the cosmic-ray positron fraction with energy and the muon gyromagnetic ratio ($g - 2$) measurement [3]. From the experimental point of view, the dark photon is characterized by two a priori unknown parameters, the mixing parameter ϵ and the mass $m_{A'}$. The A' production and the subsequent decay can be obtained from the following decay chain:

$$K^\pm \rightarrow \pi^\pm \pi^0, \pi^0 \rightarrow \gamma A', A' \rightarrow e^+ e^-$$

with three charged particles and a photon in the final state. The expected branching fraction of the π^0 decay is [4]

$$B(\pi^0 \rightarrow \gamma A') = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2} \right)^3 \times B(\pi^0 \rightarrow \gamma \gamma) \quad (1)$$

which is kinematically suppressed as $m_{A'}$ approaches m_{π^0} . In the mass range $2m_e \ll m_{A'} < m_{\pi^0}$ accessible in this analysis, the dark photon is below threshold for all decays into SM fermions except

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$A' \rightarrow e^+e^-$, while the allowed loop-induced decays ($A' \rightarrow 3\gamma, A' \rightarrow \nu\bar{\nu}$) are strongly suppressed. Therefore, assuming that the dark photon decay only in SM particles, $B(A' \rightarrow e^+e^-) \simeq 1$. The expected total dark photon decay width is [5]

$$\Gamma(A' \rightarrow e^+e^-) = \frac{1}{3}\alpha\epsilon^2 m_{A'} \sqrt{1 - \frac{4m_e^2}{m_{A'}^2}} \left(1 + \frac{2m_e^2}{m_{A'}^2}\right)$$

It follows that, for $2m_e \ll m_{A'} < m_{\pi^0}$, the dark photon mean proper lifetime $\tau_{A'}$ satisfies the relation

$$c\tau_{A'} \simeq 0.8\mu\text{m} \times \left(\frac{10^{-6}}{\epsilon^2}\right) \times \left(\frac{100\text{MeV}}{m_{A'}}\right)$$

The NA48/2 analysis is performed assuming that the dark photon decays at the production point (*prompt decay*), which is valid for sufficiently large values of the mass ($m_{A'} > 10\text{MeV}/c^2$) and the mixing parameter ($\epsilon^2 > 5 \times 10^{-7}$). In this condition the dark photon signature is identical to the Dalitz decay $\pi^0 \rightarrow \gamma e^+e^-$, which therefore represents an irreducible background and determines the sensitivity. The largest π_D^0 sample is obtained through the reconstruction of $K^\pm \rightarrow \pi^\pm\pi^0$ and $K^\pm \rightarrow \mu^\pm\pi^0\nu$ decays (denoted $K_{2\pi}$ and $K_{\mu 3}$). In Addition, the $K^\pm \rightarrow \pi^\pm\pi^0\pi^0$ decay (denoted $K_{3\pi}$) is considered as a background in the $K_{\mu 3}$ sample.

2 The NA48/2 experiment

The NA48/2 beam line has been designed to deliver simultaneous narrow momentum band K^+ and K^- beams following a common beam axis derived from the primary 400 GeV/c protons extracted from the CERN SPS. Secondary beams with central momenta of (60 ± 3) GeV/c (r.m.s.) were used. The beam kaons decayed in a fiducial decay volume contained in a 114 m long cylindrical vacuum tank. The momenta of charged decay products were measured in a magnetic spectrometer, housed in a tank filled with helium placed after the decay volume. The spectrometer comprised four drift chambers (DCHs), two upstream and two downstream of a dipole magnet which provided a horizontal transverse momentum kick of 120 MeV/c to singly-charged particles. Each DCH was composed of eight planes of sense wires. A plastic scintillator hodoscope (HOD) producing fast trigger signals and providing precise time measurements of charged particles was placed after the spectrometer. Further downstream was a liquid krypton electromagnetic calorimeter (LKr), an almost homogeneous ionization chamber with an active volume of 7 m^3 of liquid krypton, $27X_0$ deep, segmented transversally into 13248 projective $2 \times 2\text{ cm}^2$ cells and with no longitudinal segmentation. The LKr information is used for photon measurements and charged particle identification. An iron/scintillator hadronic calorimeter and muon detectors were located further downstream. A dedicated two-level trigger was in operation to collect three-track decays with an efficiency of about 98%. A detailed description of the detector can be found in Ref. [6].

3 Event selection

The full NA48/2 data sample is used for the analysis. The $K_{2\pi}$ and $K_{\mu 3}$ with the following $\pi^0 \rightarrow \gamma e^+e^-$ event selection requires a three-track vertex reconstructed in the fiducial decay region formed of a pion or muon candidate track and two opposite-sign electron ($e^\pm$) candidate tracks. Charged particle identification is based on the ratio of energy deposition in the LKr calorimeter (E) to the momentum measured by the spectrometer (p). Pions and muons are kinematically constrained to the momentum range above $5\text{ GeV}/c$, while the momentum spectra of electrons originating from π^0 decays are soft,

Figure 1. Data and Monte Carlo reconstructed $\pi^+\pi_D^0$ invariant mass for the event passing the $K_{2\pi}$ selection (left). Data and Monte Carlo reconstructed invariant mass for the event passing the $K_{\mu 3}$ selection (right). The arrows represent the selection cuts.

Figure 2. Data and Monte Carlo reconstructed m_{ee} invariant mass for the event passing the $K_{2\pi}$ selection (left). Data and Monte Carlo reconstructed m_{ee} invariant mass for the event passing the $K_{\mu 3}$ selection (right).

peaking at 3 GeV/c. Therefore, $p > 5 \text{ GeV/c}$ and $E/p < 0.85$ ($E/p < 0.4$) are required for the pion (muon) candidate, while $p > 2.75 \text{ GeV/c}$ and $(E/p)_{\min} < E/p < 1.15$, where $(E/p)_{\min} = 0.80$ for $p < 5 \text{ GeV/c}$ and $(E/p)_{\min} = 0.85$ otherwise, are required for the electron candidates. Furthermore, a single insulated LKr energy deposition cluster is required and considered as the photon candidate. The reconstructed invariant mass of the $e^+e^-\gamma$ system is required to be compatible with the π^0 mass, $|m_{e^+e^-\gamma} - m_{\pi^0}| < 8 \text{ MeV}/c^2$ (this interval corresponds to ± 5 times the resolution on $m_{e^+e^-\gamma}$).

For the $K_{2\pi}$ selection, the reconstructed invariant mass of the $\pi^\pm e^+e^-\gamma$ (figure 1) system should be compatible with the $K^\pm$ mass, $474 \text{ MeV}/c^2 < m_{\pi^\pm e^+e^-\gamma} < 514 \text{ MeV}/c^2$. For the $K_{\mu 3}$ selection, the squared missing mass $m_{\text{miss}}^2 = (P_K - P_\mu - P_{\pi^0})^2$ (figure 1) should be compatible with the neutrino mass ($|m_{\text{miss}}^2| < 0.01 \text{ GeV}^2/c^4$), where P_μ and P_{π^0} are the reconstructed $\mu^\pm$ and π^0 four-momenta, and P_K is the nominal kaon four-momentum.

At the end of the two selections a sample of 1.38×10^7 (0.31×10^7) fully reconstructed π_D^0 decay candidates coming from $K_{2\pi}$ ($K_{\mu 3}$) with a negligible background is selected. Correcting the observed number of candidates for acceptance and trigger efficiency, the total number of $K^\pm$ decays in the 98 m long fiducial decay region for the analysed data sample is found to be $N_K = (1.57 \pm 0.05) \times 10^7$, where the quoted error is dominated by the external uncertainty on the π_D^0 decay branching fraction. The reconstructed e^+e^- invariant mass spectra are displayed in figure 2. In addition to the above individual $K_{2\pi}$ and $K_{\mu 3}$ selections, a *joint* dark photon selection is also considered: an event passes the joint selection if it passes either the $K_{2\pi}$ or the $K_{\mu 3}$ selection. The acceptance of the joint selection for any process is equal to the sum of acceptances of the two mutually exclusive individual selections.

4 The π^0 Dalitz simulation

The π_D^0 decay is simulated using the following lowest-order differential decay rate

$$\frac{d^2\Gamma}{dx dy} = \Gamma_0 \frac{\alpha}{\pi} |F(x)|^2 \frac{(1-x)^3}{4x} \left(1 + y^2 + \frac{r^2}{x}\right)$$

with x and y , two kinematic variables, defined as

$$x = \frac{(q_1 + q_2)^2}{m_\pi^2} = \frac{m_{ee}^2}{m_{\pi^0}^2} \quad y = \frac{2p(q_1 - q_2)}{m_{\pi^0}(1-x)}$$

$r = 2m_e/m_{\pi^0}$, q_1 , q_2 and p are the four-momenta of the electrons ($e^\pm$) and the neutral pion, Γ_0 is the rate of the $\pi^0 \rightarrow \gamma\gamma$ decay, and $F(x)$ is the pion transition form factor (TFF).

Radiative corrections to the differential rate are implemented following the classical approach of Mikaelian and Smith [7]: the differential decay rate is modified using the following formula

$$\frac{d^2\Gamma^{\text{rad}}}{dx dy} = \delta(x, y) \frac{d^2\Gamma}{dx dy}$$

which does not account for the emission of inner bremsstrahlung photons.

The TFF is conventionally parameterized as $F(x) = 1 + ax$. The transition form factor slope parameter a is expected from vector meson dominance models to be $a \simeq 0.03$, and detailed theoretical calculations based on dispersion theory yield $a = 0.0307 \pm 0.0006$ [8]. Experimentally, the PDG average $a = 0.032 \pm 0.004$ [9] is determined mainly from a $e^+e^- \rightarrow e^+e^-\pi^0$ rate measurement in the space-like region by the CELLO experiment [10]. The precision on the used radiative corrections to the π_D^0 decay is limited: in particular, the missing correction to the measured TFF slope due to two-photon exchange is estimated to be $\Delta a = +0.005$ [11]. Therefore the background description cannot benefit

Figure 3. Numbers of observed data events and expected π_D^0 background events passing the joint selection (indistinguishable in a logarithmic scale), estimated uncertainties and obtained upper limits at 90% CL on the numbers of dark photon candidates (N_{DP}) for each mass value $m_{A'}$ (left). Estimated local significance of the dark photon signal for each A' mass value (right).

from the precise inputs on the TFF slope [8, 9], and an “effective” TFF slope obtained from a fit to the data m_{ee} spectrum itself is used to obtain a satisfactory background description (as quantified by a χ^2 test) over the range $m_{ee} > 8 \text{ MeV}/c^2$ used for the dark photon search. The low m_{ee} region is not considered for the search as the acceptance computation is less robust due to the steeply falling geometrical acceptance at low m_{ee} and decreasing electron identification efficiency at low momentum.

5 Search for the dark photon

A scan for a dark photon signal in the mass range $9 \text{ MeV}/c^2 \leq m_{A'} < 120 \text{ MeV}/c^2$ is performed. The lower extent of the considered mass range is determined by the limited precision of MC simulation of background at low mass, while at the upper limit of the mass range the signal acceptance drops to zero. The mass step of the scan and the width of the dark photon signal mass window around the assumed mass are determined by the resolution δm_{ee} on the e^+e^- invariant mass. The resolution on m_{ee} as a function of m_{ee} evaluated with MC simulation is parameterized as $\sigma_m(m_{ee}) = 0.067 \text{ MeV}/c^2 + 0.0105 \cdot m_{ee}$, and varies from $0.16 \text{ MeV}/c^2$ to $1.33 \text{ MeV}/c^2$ over the mass range of the scan. The mass step of the scan is set to be $\sigma_m/2$, while the signal region mass window for each dark photon mass hypothesis is defined as $\pm 1.5\sigma_m$ around the assumed mass. The mass window width has been optimised with MC simulations to obtain the highest sensitivity to the dark photon signal, determined by a trade-off between π_D^0 background fluctuation and signal acceptance.

For each considered dark photon mass value, the number of observed data events N_{obs} passing the joint selection is compared to the expected number of background events N_{exp} . The latter is evaluated from MC simulations, corrected for the trigger efficiency measured from control data samples passing the joint selection. The numbers of observed and expected events for each mass value and their estimated uncertainties δN_{obs} and δN_{exp} are shown in figure 3. The uncertainty $\delta N_{obs} = \sqrt{N_{obs}}$ is statistical, while the uncertainty δN_{exp} has contributions from the limited size of the generated MC samples and

Figure 4. Acceptances of the joint dark photon selection for $K_{2\pi}$, $K_{\mu 3}$ and $K_{3\pi}$ depending on the assumed DP mass, evaluated with MC simulations. The $K_{3\pi}$ acceptance is scaled by a factor of 10 for visibility (left). Obtained upper limits on $B(\pi^0 \rightarrow A'\gamma)$ at 90% CL for each A' mass value (right).

the statistical errors on the trigger efficiencies measured in the dark photon signal region. The local statistical significance of the dark photon signal for each mass value estimated as

$$Z = (N_{obs} - N_{exp}) / \sqrt{(\delta N_{obs})^2 + (\delta N_{exp})^2}$$

Confidence intervals at 90% CL for the number of $A' \rightarrow e^+e^-$ decay candidates (N_{DP}) in each mass hypothesis are computed from N_{obs} , N_{exp} and δN_{exp} using the Rolke–López method [12] assuming Poissonian (Gaussian) errors on the numbers of observed (expected) events.

Upper limits at 90% CL on the branching fraction $B(\pi^0 \rightarrow A'\gamma)$ for each dark photon mass value with the assumption $B(A' \rightarrow e^+e^-) = 1$ (which is a good approximation for $m_{A'} < 2m_\mu$ if A' decays to SM fermions only) are computed using the relation

$$B(\pi^0 \rightarrow A'\gamma) = \frac{N_{DP}}{N_K e_1 e_2 [B(K_{2\pi}) A_{DP}(K_{2\pi}) + B(K_{\mu 3}) A_{DP}(K_{\mu 3}) + 2B(K_{3\pi}) A_{DP}(K_{3\pi})]}$$

where $A_{DP}(K_{2\pi})$, $A_{DP}(K_{\mu 3})$ and $A_{DP}(K_{3\pi})$ are the acceptances of the joint dark photon selection for $K_{2\pi}$, $K_{\mu 3}$ and $K_{3\pi}$ decays, respectively, followed by the prompt $\pi^0 \rightarrow A'\gamma$, $A' \rightarrow e^+e^-$ decay chain. The trigger efficiencies e_1 and e_2 are taken into account neglecting their variations over the m_{ee} invariant mass, variations measured to be at the level of a few permille. Event distributions in the angle between e^+ momentum in the e^+e^- rest frame and the e^+e^- momentum in the π^0 rest frame are identical for the decay chain involving the dark photon ($\pi^0 \rightarrow A'\gamma$, $A' \rightarrow e^+e^-$) and the π^0_D decay, up to a negligible effect of the radiative corrections that should not be applied in the former case (found to influence the acceptance at the level below 1% in relative terms). Therefore dark photon acceptances are evaluated using the MC samples produced for background description, and no dedicated MC productions are required. The resulting upper limits on $B(\pi^0 \rightarrow A'\gamma)$ and signal acceptances are shown in figure 4. The upper limits are $O(10^{-6})$ and do not exhibit a strong dependence on the A' mass.

Figure 5. The NA48/2 preliminary upper limits at 90% CL on the mixing parameter ϵ^2 versus the A' mass, compared to the other published exclusion limits from meson decay, beam dump and e^+e^- collider experiments. Also shown are the band for the muon $(g-2)$ and the region excluded by the electron $g-2$ measurement.

Upper limits at 90% CL on the mixing parameter ϵ^2 for each dark photon mass value calculated from the $B(\pi^0 \rightarrow A'\gamma)$ upper limits using equation 1 are shown in figure 5, together with the constraints from the SLAC E141 and FNAL E774 [13], KLOE [14], WASA [15], HADES [16], A1 [17], APEX [18] and BaBar [19] experiments. Also shown is the band in the $(m_{A'}, \epsilon^2)$ plane where the discrepancy between the measured and calculated muon $(g-2)$ values falls into the $\pm 2\sigma$ range due to the dark photon contribution, as well as the region excluded by the electron $(g-2)$ measurement [3, 20]. The obtained upper limits on ϵ^2 represent an improvement over the existing data in the dark photon mass range $9 - 70 \text{ MeV}/c^2$, and exclude the whole favoured region by muon $g-2$ [21]. The most stringent limits (2×10^{-7}) are achieved at $m_{A'} \sim 10 \text{ MeV}/c^2$. The sensitivity of the prompt A' decay search is limited by the irreducible π_D^0 background. The achievable upper limit on ϵ^2 scales as the inverse square root of the integrated beam flux, which means that the possible improvements to be made with this technique using larger future $K^\pm$ samples are modest.

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