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Search for Dark Photon at NA48/2, and measurement of π^0 form factor

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Abstract. The NA48/2 experiment at CERN performed a search for the dark photon (A') via the decay chain $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+ e^-$. Using a sample of $\sim 1.7 \cdot 10^7$ neutral pions tagged from $K^\pm \rightarrow \pi^\pm \pi_D^0$ and $K^\pm \rightarrow \mu^\pm \pi_D^0 \nu$ decays collected in 2003-04 no signal is observed. The limits in the plane dark photon mixing parameter ε^2 versus its mass $m_{A'}$ are reported. The NA62-RK experiment collected, during the 2007 data taking, a large sample of neutral pion Dalitz decays with a trigger optimised for electrons final states with respect to NA48/2 one. We report the measurement of the π^0 electromagnetic transition form factor (TFF) slope parameter (a) based on a sample of $\sim 1 \cdot 10^6$ π_D^0 decays. The preliminary measured value $a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \cdot 10^{-2}$ is compatible with theoretical expectations and previous measurements.

1. Introduction

The NA48/2 beam line was designed to deliver simultaneous narrow momentum band K^+ and K^- beams with central momenta of 60 GeV/c derived from the 400 GeV/c protons extracted from the CERN SPS. The beam kaons decayed in an 114 m long fiducial volume contained in a cylindrical vacuum tank. The momenta of charged decay products were measured by a magnetic

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spectrometer consisting of four drift chambers (DCHs), two upstream and two downstream of a dipole magnet. The magnet provided a horizontal transverse momentum kick to charged particles of 120 MeV/c. Each DCH was made of eight planes of sense wires. Downstream of the spectrometer a plastic scintillator hodoscope producing fast trigger signals and providing precise time measurements of charged particles was placed. Further downstream was a liquid krypton electromagnetic calorimeter (LKr), an almost homogeneous ionization chamber with an active volume of 7 m^3 , $27X_0$ deep, segmented transversally into 13248 projective $2 \times 2 \text{ cm}^2$ cells and with no segmentation along the beam axis. The calorimeter information is used for photon energy measurements and charged particle identification. An iron/scintillator hadronic calorimeter and muon detectors were located further downstream. A description of the detector can be found in [1]. The NA62-RK experiment collected data during 2007, using the NA48/2 detector, aiming at measuring the ratio R_K of the rates of the leptonic kaon decays. The experiment used modified beam central momentum of 74 GeV/c and different trigger conditions optimized to collect electrons.

2. Search for the Dark Photon in π^0 decays

The hypothesis that the dark matter can be hiding in the so-called “dark sectors” has become more and more popular in recent years, attracting an increasing interest both in experimental searches and theoretical studies[3]. In this set of models, the Standard Model (SM) and the dark sector are connected by “mediators”, particles with quantum numbers of both SM and dark sector forces. In the most general $U(1)$ extension of the SM the mediator can kinetically mix with the photon [2] and is commonly called “dark photon” (DP). Due to the mixing with the standard model photon, the DP can be directly produced in collisions of an electron or proton with a target, and in the decays of mesons (π^0 , η , ϕ) containing a γ in the final state[4]. The DP decay modes depend on its mass and on the hypothesis on the dark sector particle mass spectrum. The most commonly used are to consider the DP the lightest state in the dark sector and that it decays to SM particles, “visible decays”. NA48/2 performed a search for the dark photon in π^0 decays exploiting the process $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$. During the 2003 and 2004 data taking periods NA48/2 accumulated the world largest sample of tagged π^0 decays, $\sim 5 \cdot 10^{10}$, originating from $K^\pm \rightarrow \pi^\pm \pi^0$ and $K^\pm \rightarrow \mu^\pm \pi^0 \nu_\mu$ kaon decays.

The predicted branching fraction of the π^0 decay to $\gamma A'$ is expressed in term of the dark sector coupling strength ε and the DP mass $m_{A'}$ as follows [6]:

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

with a strong kinematic suppression of the decay rate for DP masses approaching m_{π^0} . In the mass range of interest for the present analysis, $2m_e < m_{A'} < m_{\pi^0}$, under the hypothesis of visible decays, the $\mathcal{B}(A' \rightarrow e^+e^-)$ is ≈ 1 . The sensitivity of the NA48/2 data set is unfortunately limited by the $\pi_D^0 \rightarrow e^+e^-\gamma$ decay, which represents an irreducible background producing a signature identical to that of the DP. In fact, in the accessible parameter range ($m_{A'} > 10 \text{ MeV}/c^2$ and $\varepsilon^2 > 5 \times 10^{-7}$), the maximum DP mean path does not exceed 10 cm and the DP can not be distinguished from genuine π_D^0 decays which decay promptly. On the other hand, the NA48/2 3-track vertex reconstruction does not introduce significant acceptance losses for DP events as the typical resolution on the vertex longitudinal coordinate is $\approx 1 \text{ m}$.

The full NA48/2 data sample is used in the present analysis. The event selection criteria developed are very similar for both $K^\pm \rightarrow \pi^\pm \pi_D^0$ ($K_{2\pi D}$) and $K^\pm \rightarrow \mu^\pm \pi^0 \nu_\mu$ ($K_{\mu 3D}$) tagged π^0 decays. Both require a three-track vertex reconstructed in the fiducial decay region and two opposite-sign electrons (e^\pm) candidate tracks. Charged particle identification is based on the ratio of energy deposition in the LKr calorimeter to the momentum measured by

the spectrometer. In addition, a single isolated LKr energy deposition cluster is required as the photon candidate. The number of π_D^0 decay candidates reconstructed with the joint π^0 decay selection is $1.69 \cdot 10^7$. The reconstructed invariant mass of the $\pi^\pm\pi_D^0$ system and the squared missing mass of the $\mu^\pm\pi_D^0$ (the neutrino invariant mass squared) are presented for the corresponding decay modes in the left column of (Fig. 1). The width of the DP is expected to be very small, due to the ϵ^2 suppression of the coupling to SM particles. For this reason the characteristic signature of its decay into lepton pair is a very narrow peak in the di-electron invariant mass spectra, that are shown in the right column of (Fig. 1) for both the selected data samples.

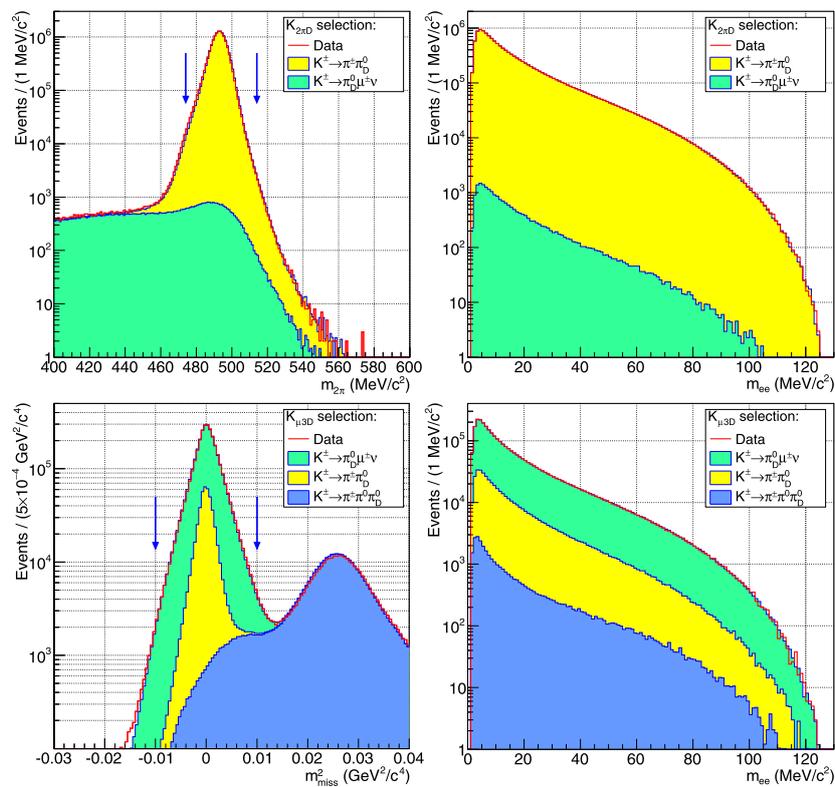


Figure 1. Left) Reconstructed $\pi^\pm\pi_D^0$ invariant mass (top) and $\mu^\pm\pi_D^0\nu$ missing mass (bottom) distributions of the data and simulated samples. The selection condition is illustrated with blue arrows.

Right) Invariant di-lepton mass distributions for the selected data samples. A dark photon signal would manifest itself as a spike in the m_{ee} distributions.

A scan for a DP signal is performed with 404 tentative DP masses in the range $9 \text{ MeV}/c^2 < m_{A'} < 120 \text{ MeV}/c^2$, limited at the lower boundary by the reduced accuracy of the π_D^0 background simulation at low e-e mass, and on the higher boundary by the kinematic suppression of the $\pi^0 \rightarrow \gamma A'$ decay in Eq. 1. For each considered DP mass value, the number of data candidates N_{obs} passing the joint DP selection, is compared to the estimated number of background events N_{exp} evaluated with MC simulations. The local statistical significance of the DP signal for each mass hypothesis is presented in Fig. 2. Its value never exceeds 3σ , therefore no DP signal is observed. For each DP mass value the upper limits at 90% CL on the number of A' candidates

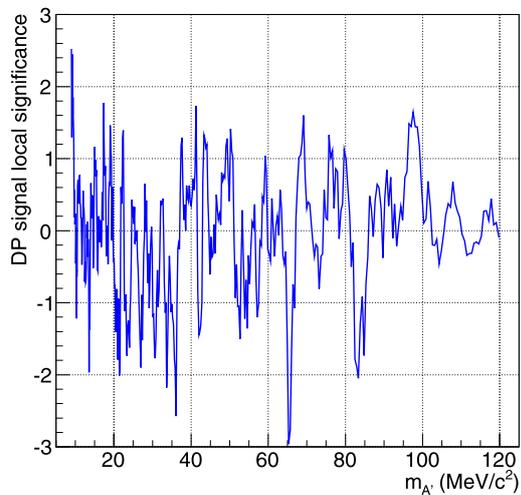


Figure 2. Local significance of the DP signal for each A' mass hypothesis. Neighbouring values are strongly correlated since the mass step of the scan is much smaller than the width of the signal window[5].

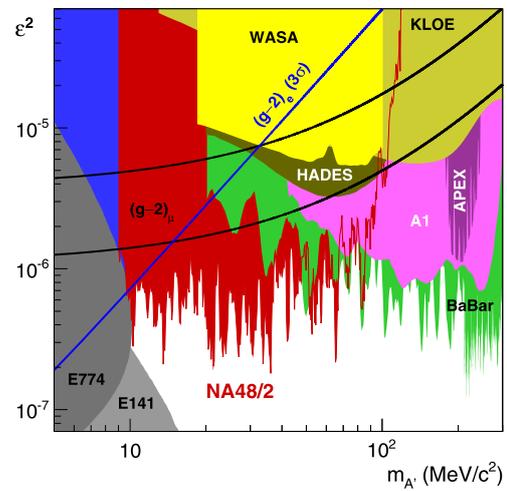


Figure 3. The NA48/2 upper limits at 90% CL on the mixing parameter ε^2 versus the DP mass $m_{A'}$, compared to the other exclusion limits[5].

(N_{DP}), computed from N_{obs} , N_{exp} and δN_{exp} using the frequentist Rolke-Lpez method[7], is translated into the corresponding branching fraction limit $\mathcal{B}(\pi^0 \rightarrow \gamma A')$ using the relation:

$$\mathcal{B}(\pi^0 \rightarrow \gamma A') = \frac{1}{N_K \epsilon} \frac{N_{DP}}{\left[\mathcal{B}(K_{2\pi})A(K_{2\pi}) + \mathcal{B}(K_{\mu 3})A(K_{\mu 3}) + 2\mathcal{B}(K_{3\pi})A(K_{3\pi}) \right]}. \quad (2)$$

where $A(K_{2\pi}, K_{\mu 3}, K_{3\pi})$ are the acceptances of the joint DP selection for the corresponding K decay followed by the prompt $A' \rightarrow ee$ decay, ϵ is the trigger efficiency, and $N_K = (1.57 \pm 0.05) \times 10^{11}$ [5] is the total number on kaon decays collected by NA48/2. Upper limits at 90% CL on the mixing parameter ε^2 , calculated from Eq. 1 for each DP mass value $m_{A'}$, are shown in Fig. 3 together with a collection of present constraints[5]. The band in between the two black lines, where the inconsistency of theoretical and experimental values of the muon (g-2) reduces to less than 2 standard deviations, is also shown as well as the region above the blue line excluded by the electron (g-2) measurement.

The search presented represents the most stringent upper limit on the mixing parameter ε^2 in the mass range 9-70 MeV/c². In combination with other experimental limits, under the assumption that DP couples to quarks and decays to SM particles only, this result completes the exclusion of the region of parameter space which could solve the g-2 anomaly, ruling out the DP as a possible explanation.

3. Measurement of the π^0 Form Factor slope

The neutral pion, composed of only u and d quarks, is the lightest of all the mesons and is, therefore, a particularly interesting field to study the low energy behaviour of the SM strong interaction. The π^0 decays electromagnetically to a pair of photons with a Branching Fraction of $(98.823 \pm 0.034)\%$ while in almost all the remaining cases decays into an electron-positron

pair and a photon. In this decay mode $\pi^0 \rightarrow e^+e^-\gamma$, one of the two photons acquires an off-shell mass greater than ~ 1 MeV and then decays into an electron-positron pair. In the theoretical treatment of this decay the most common approach is to factorize the differential decay width into a point-like part and a Form Factor (FF), encoding the information about the particle structure without an explicit description of the underlying physics.

3.1. The π^0 Transition Form Factor slope

The π_D^0 decay width is parameterised in term of two independent kinematic variables $x = (M_{e^+e^-}/m_{\pi^0})^2$, $y = 2p_{\pi^0}(p_{e^+} - p_{e^-})/(m_{\pi^0}^2(1-x))$ as follows:

$$\frac{1}{\Gamma(\pi_{\gamma\gamma}^0)} \frac{d^2\Gamma(\pi_D^0)}{dx dy} = \frac{\alpha}{4\pi} \frac{(1-x)^3}{x} (1+y^2 + \frac{r^2}{x}) |F(x)|^2 (1 + \delta(x, y)) \quad (3)$$

where $r^2 = (2m_e/m_{\pi^0})^2$. The first term represents the point-like approximation, $F(x)$, the Transition Form Factor (TFF), while the last term $(1+\delta(x, y))$ the radiative corrections due to the interaction of the two electrons in the final state.

In the allowed kinematic region for the π_D^0 decay, $F(x)$ is expected to vary slowly and can be described with a linear approximation:

$$F(x) = 1 + ax \quad (4)$$

where a is the so-called TFF slope parameter. In the vector meson dominance (VMD) approach, first proposed by Gell-Mann and Zachariasen [8], $F(x)$ is dominated by ρ and ω mesons contributions, resulting in a predicted value of $a \approx m_{\pi^0}^2(m_\rho^{-2} + m_\omega^{-2})/2 \approx 0.03$.

3.2. NA62-RK Transition Form Factor slope measurement

NA62-RK experiment has performed the most precise measurement to date of the form factor slope a based on a sample 1.05×10^6 π_D^0 decays collected during the 2007 data taking period. The effect of changing the value of the parameter a is very small in the distribution of the di-electron invariant mass, therefore a proper treatment of the radiative corrections and a large unbiased data sample are necessary to perform a precise measurement. The radiative corrections to the π_D^0 decay were originally computed in NA62 by interpolating the table of points in the (x, y) plane provided by the Mikaelian and Smith paper[9]. Recent revision of the original calculation by Husek et al. [10] provided the NA62 experiment with a code for the exact $\delta(x, y)$ computation in any phase space point. The new calculation also adds to the original one the one-loop one-photon irreducible contribution, and is able to produce extra radiated photons, which can play a significant role in the determination of experimental acceptance.

Since the π^0 electromagnetic TFF does not depend on the y Dalitz variable, we can integrate the differential decay width in Eq.3 over y and obtain the slope parameter only from the reconstructed distribution of the x Dalitz variable:

$$\frac{1}{\Gamma(\pi_{\gamma\gamma}^0)} \frac{d^2\Gamma(\pi_D^0)}{dx} = \frac{2\alpha}{3\pi} \frac{(1-x)^3}{2x} \left(1 + \frac{r^2}{2x}\right) \sqrt{\left(1 - \frac{r^2}{x}\right)} (1 + \delta(x, y))(1 + ax)^2 \quad (5)$$

The extraction of the TFF slope a is performed by comparing the x data distribution with different MC spectra obtained varying the value of the TFF slope parameter. The best value for a is chosen by selecting the MC sample showing the best agreement with the x data distribution.

A tagging procedure for π_D^0 decays similar to the one already described for the DP searches has been used to select the NA62-RK data sample. Dalitz decays of the π^0 are tagged using $K_{2\pi D}$ and $K_{\mu 3 D}$ kaon decays profiting of the trigger conditions optimised for electrons in the NA62-RK experiment. In addition, the total energy deposit in the calorimeter (of e^+ , e^- and

γ) has to exceed 14 GeV and at least one of the leptons tracks is required to have momentum above 5.5 GeV/c. These cuts are intended in order to just select the region of high trigger efficiency where the agreement with the MC is satisfactory. Since the acceptance of events in the region $x \leq 0.01$ is not well reproduced in the simulation, the reconstructed x variable has to be greater than 0.01. After all cuts, a data sample of 1.05×10^6 candidates was selected. Candidate events are divided into 20 equipopulous bins and a χ^2 minimisation is used to select

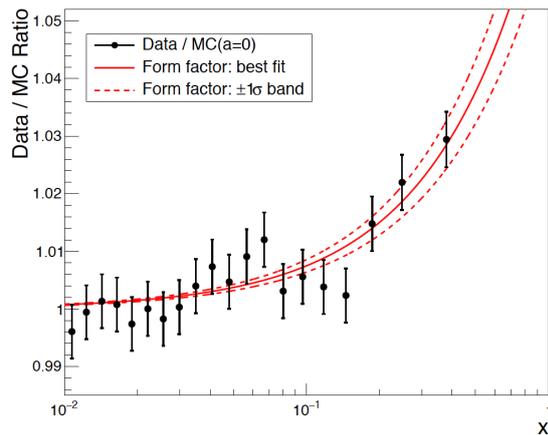


Figure 4. Result of the transition from factor slope fit. Black dots represent data/MC ratio with no form factor slope $a=0$.

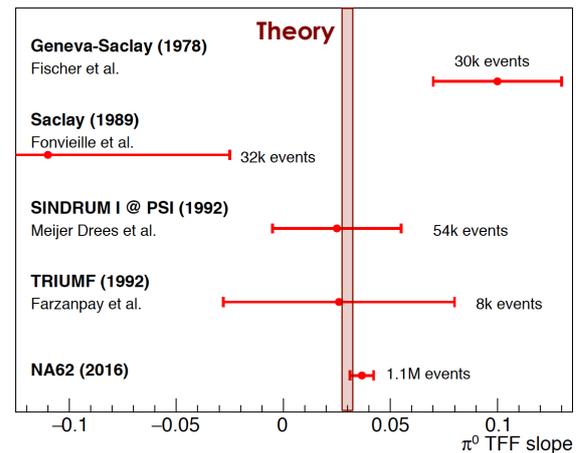


Figure 5. Comparison of the NA62-RK preliminary measurement of the TFF slope with other experiments and theoretical expectation band.

the best the data/MC histogram comparison. The preliminary value of a obtained by the fit is:

$$a = (3.70 \pm 0.53_{stat} \pm 0.36_{syst}) \times 10^{-2} = (3.70 \pm 0.64) \times 10^{-2} \quad (6)$$

with a $\chi^2/\text{d.o.f} = 52.5/49$. An illustration of the fit to the data Motecarlo ratio is shown Fig. 4. The solid red line represents the form factor best fit while the dashed red lines shows the $\pm 1\sigma$ uncertainty band. The NA62-RK preliminary result improves the precision on the π^0 TFF in the time-like momentum region compared with previous measurements [11, 12, 14, 13] as shown in Fig. 5 and is in good agreement with theoretical expectations. The analysis is at an advanced state and the final result is expected to be submitted for publication in the near future.

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