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Neutral pion form factor measurement by the NA62 experiment

Michal Zamkovsky
Speaker, Institute of Particle and Nuclear Physics, Charles University
E-mail: `michal.zamkovsky@cern.ch`

F Ambrosino, A Antonelli, G Anzivino, R Arcidiacono, W Baldini, S Balev, J R Batley, M Behler, S Bifani, C Biino, A Bizzeti, T Blazek, B Bloch-Devaux, G Bocquet, V Bolotov, F Bucci, N Cabibbo, M Calvetti, N Cartiglia, A Ceccucci, P Cenci, C Cerri, C Cheshkov, J B Chze, M Clemencic, G Collazuol, F Costantini, A Cotta Ramusino, D Coward, D Cundy, A Dabrowski, G DAgostini, P Dalpiaz, C Damiani, H Danielsson, M De Beer, G Dellacasa, J Derr, H Dibon, D Di Filippo, L DiLella, N Doble, V Duk, J Engelfried, K Eppard, V Falaleev, R Fantechi, M Fidecaro, L Fiorini, M Fiorini, T Fonseca Martin, P L Frabetti, A Fucci, S Gallorini, L Gatignon, E Gersabeck, A Gianoli, S Giudici, A Gonidec, E Goudzovski, S Goy Lopez, E Gushchin, B Hallgren, M Hita-Hochgesand, M Holder, P Hristov, E Iacopini, E Imbergamo, M Jeitler, G Kalmus, V Kekelidze, K Kleinknecht, M Koval, V Kozhuharov, W Kubischta, V Kurshetsov, G Lamanna, C Lazzeroni, M Lenti, E Leonardi, L Litov, N Lurkin, D Madigozhin, A Maier, I Mannelli, F Marchetto, G Marel, M Markytan, P Marouelli, M Martini, L Masetti, P Massarotti, E Mazzucato, A Michetti, I Mikulec, M Misheva, N Molokanova, E Monnier, U Moosbrugger, C Morales Morales, M Moulson, S Movchan, D J Munday, M Napolitano, A Nappi, G Neuhofer, A Norton, T Numao, V Obraztsov, V Palladino, M Patel, M Pepe, A Peters, F Petrucci, M C Petrucci, B Peyaud, R Piandani, M Piccini, G Pierazzini, I Polenkevich, I Popov, Y Potrebenikov, M Raggi, B Renk, F Retire, P Riedler, A Romano, P Rubin, G Ruggiero, A Salamon, G Saracino, M Savri, M Scarpa, V Semenov, A Sergi, M Serra, M Shieh, S Shkarovskiy, M W Slater, M Sozzi, T Spadaro, S Stoynev, E Swallow, M Szleper, M Valdata-Nappi, P Valente, B Vallage, M Velasco, M Veltri, S Venditti, M Wache, H Wahl, A Walker, R Wanke, L Widhalm, A Winhart, R Winston, M D Wood, S A Wotton, O Yushchenko, A Zinchenko and M Ziolkowski

Abstract. The NA62 experiment at CERN collected a large sample of charged kaon decays with a highly efficient trigger for decays into electrons in 2007. The kaon beam represents a source of tagged neutral pion decays in vacuum. A measurement of the electromagnetic transition form factor slope of the neutral pion in the time-like region from ~1 million fully reconstructed π^0 Dalitz decay is presented. The limits on dark photon production in π^0 decays from the earlier kaon experiment at CERN, NA48/2, are also reported.

Introduction

The NA48/2 experiment at the CERN SPS recorded a sample of 2×10^{11} charged kaon decays in 2003-04. The following NA62 experiment collected a ten times smaller sample of $\mathrm{K}^{\pm}$ in 2007 and was using the NA48 detector [1] and a modified beam line [2]. This paper reports on the measurements of neutral pion physics on NA62 and NA48/2, namely the measurement of the slope of the π^0 electromagnetic transition form factor from a sample of $\pi^0 \to e^+e^-\gamma$ decays and the search for the dark photon in the $\pi^0 \to \gamma A'$ decay.

1. Experimental setup

Narrow momentum band $\mathrm{K}^{\pm}$ beams with central momentum 60 (74) GeV/c, with $\delta \mathrm{P_K}/\mathrm{P_K} \sim 1\%$ (rms), were extracted from 400 GeV/c proton beam for NA48/2 (NA62) configuration. The kaon beams were focused at the first drift chamber with ~ 10 mm transverse size. The beam flux with an intensity of $2.5 \cdot 10^7$ protons per pulse entered a decay region, where ~ 18% of kaons decayed. The decay region was 113 m long, with a diameter from 1.92 m in the first 66 m increasing to 2.4 m in the last 47 m. It was contained in an evacuated cylindrical steel tank with a volume ~ 120 m^3. The vacuum at a level $\leq 10^{-4}$ mbar avoided interactions of kaon decay products before detection. The downstream part of the vacuum tank was closed by convex hemispherical (0.8 mm thick, that corresponds to $3 \cdot 10^{-3} X_0$) Kevlar window with a radius of 1.3 m. The difference between the NA48/2 and NA62 detector setups was the presence of the KABES detector, which has been removed after NA48/2. In NA48/2 two simultaneous beams of K^+ and K^- were used, while in NA62 one beam was alternatively stopped. The fiducial region was followed by a magnetic spectrometer, consisting of four drift chambers (DCH), housed in a vessel filled with helium gas at nearly atmospheric pressure. Through the middle of DCH and following detector a beam pipe allowed the undecayed particles to continue their path in vacuum. Each DCH consisted of 8 octagonal planes with 256 grounded wires and was operated with a gas mixture of 50% Argon and 50% Ethan. The maximum drift time in a plane was 100 ns. The resolution on the spatial position of the reconstructed hit was 90 μm and the time resolution was about 700 ps. A spectrometer magnet was located between the chambers DCH2 and DCH3. It provided a momentum kick of 120 (257) MeV/c. The resolution of momentum measurement was: $\sigma_p/p = (1.02 \oplus 0.044 \cdot p)\%$ and $\sigma_p/p = (0.48 \oplus 0.009 \cdot p)$ in 2007, p in GeV/c. The spectrometer was followed by a scintillator hodoscope consisting of two planes segmented into horizontal and vertical strips achieving a very good ~ 150 ps time resolution. Further downstream was a liquid krypton calorimeter (LKr) that measured the energy of electrons and photons. The transverse segmentation into 13248 2 cm × 2 cm projective cells and the 27 radiation length thickness resulted in an energy resolution $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$ (E in GeV/c) and a transverse position resolution of 1.5 mm for 10 GeV showers. The calorimeter was followed by a muon system consisting of three scintillator planes, with an iron wall installed in front of each plane. A detailed description of the beam line, detectors and trigger is available in [1].

2. Theory

The Dalitz decay $\pi^0_D \to e^+e^-\gamma$ proceeds through the $\pi^0\gamma\gamma$ vertex with an off-shell photon. The commonly used independent kinematic variables x and y are defined in terms of particle four-momenta:

$$x = \left(\frac{M_{ee}}{m_{\pi^0}}\right)^2 = \frac{(p_{e^+}+p_{e^-})^2}{m^2_{\pi^0}}, \qquad y = \frac{2p_{\pi^0}\cdot(p_{e^+}-p_{e^-})}{m^2_{\pi^0}(1-x)}. \tag{1}$$

The x variable is the normalized invariant mass squared of the electron-positron pair, while y is related to the angles between the final state particle momenta. The kinematic limits on the variables are given by

$$r^2 \le x \le 1, \quad -\beta \le y \le \beta, \quad \text{where} \quad r = \frac{2m_e}{m_{\pi_0}} \quad \text{and} \quad \beta = \sqrt{1-\frac{r^2}{x}}. \tag{2}$$

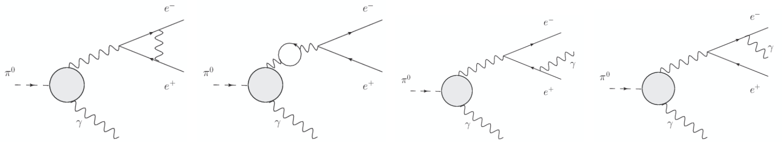
The normalized π^0_D leading order (LO) differential decay width reads:

$$\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d^2\Gamma(\pi^0_D)}{dxdy} = \frac{\alpha}{4\pi}\frac{(1-x)^3}{x}(1+y^2+\frac{r^2}{x})|F(x)|^2. \tag{3}$$

In the allowed kinematic region for the π^0_D decay, $F(x)$ is expected to vary slowly and it is sufficient to use a linear approximation $F(x) = 1 + ax$, where a is the so-called π^0 *transition form factor* (TFF) slope parameter. The expected π^0 TFF slope value from Vector Meson Dominance model, dominated by the ρ and ω mesons, is $a \approx 0.03$. The theoretical models of π^0 TFF enter hadronic light-by-light scattering contribution to $(g-2)_\mu$. For a recent overview and references see [3]. The comparison of TFF slope predictions with a model independent measurement is an important test of the theory models.

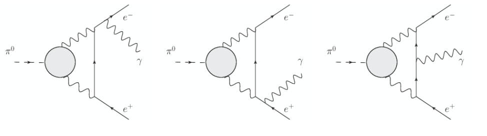
2.1. Radiative Corrections

The radiation corrections are a crucial aspect of measuring the π^0 TFF, as their effect on the differential decay rate exceed that of the TFF. The first study of radiative corrections was done in [4] and extended in [5], where the following diagrams were considered:



$\delta_{virt} + \delta_{BS}$ corrections.

The revisited and improved radiative corrections in [6] were largely triggered by and used for this analysis. They include additional second-order contributions to the internal bremsstrahlung:



$\delta_{1\gamma\mathrm{IR}}$ correction.

The contribution of the radiative corrections in the $(x,\, y)$ plane together with the separate contributions from different origins are shown in Figure 1. They enter the differential decay width through a function $\delta(x,y) = \delta_{virt} + \delta_{BS} + \delta_{1\gamma\mathrm{IR}}$ in the next-to-leading-order (NLO):

$$\frac{d^2\Gamma}{dxdy} = \frac{d^2\Gamma^{LO}}{dxdy}\left(1+\delta(x,y)\right), \qquad \delta(x,y) = \frac{d^2\Gamma^{NLO}}{dxdy}\Big/\frac{d^2\Gamma^{LO}}{dxdy}. \tag{4}$$

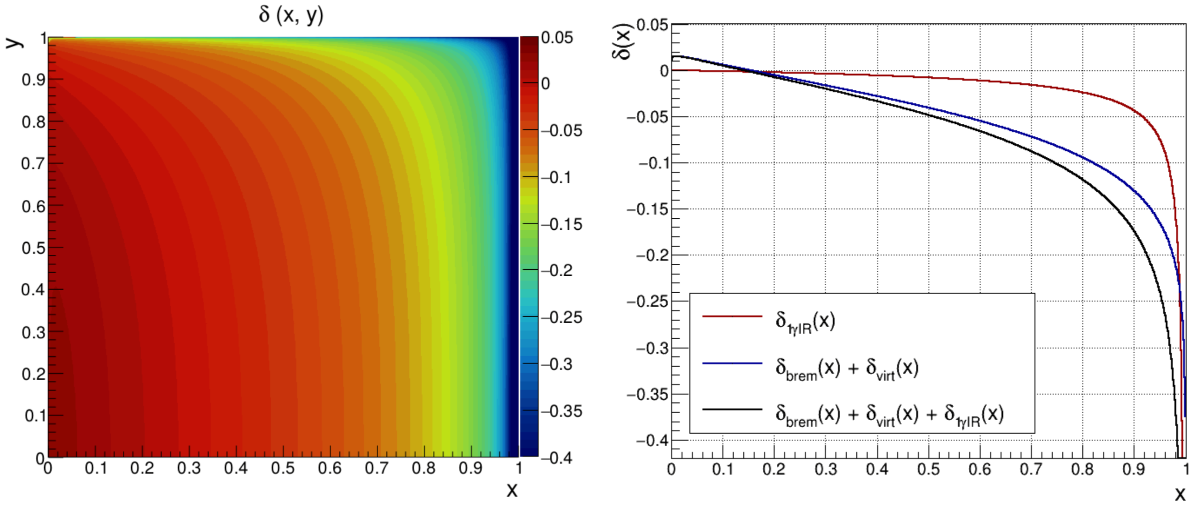


Figure 1. Left: Size of the radiative corrections to the π^0_D decay in the x, y plane. Right: Size of the radiative corrections versus x. Black line represents the total radiative correction size; blue corresponds to its component first computed in [5]; red shows the new contribution, introduced in [6].

As the π^0 TFF does not depend on the y Dalitz variable, the slope parameter is extracted from the reconstructed distribution of the x Dalitz variable. One can therefore integrate the π^0_D differential decay width in eq. 3 over y and obtain:

$$\frac{1}{\Gamma(\pi^0_{2\gamma})}\frac{d\Gamma(\pi^0_D)}{dx} = \frac{2\alpha}{3\pi}\frac{(1-x)^3}{x}(1+\frac{r^2}{2x})\sqrt{1-\frac{r^2}{x}}(1+\delta(x))(1+ax)^2, \tag{5}$$

where the TFF is described by the linear parametrization and the radiative corrections to the x distribution are included.

3. Event selection

The tagged π^0s are originating from $K^\pm \to \pi^\pm\pi^0$ decays, which branching fraction is $BR(K_{2\pi}) \approx 21\%$. In 2007, the data taking conditions were optimized for $e^\pm$ from $K^\pm \to e^\pm\nu_e$, which is favorable also for the $K^\pm \to \pi^\pm\pi^0$ with subsequent decay $\pi^0 \to \gamma e^+e^-$. During 2007 a large and clean sample of π^0_D decays was recorded, counting 1.05×10^6 events. The selection of signal events was based on the three-track topology, a photon cluster in LKr and full kinematic closure. The selection was restricted to area with Dalitz variable $x > 0.01$. Figure 2 shows the reconstructed and simulated invariant mass of π^0_D, and the distribution of the Dalitz x variable.

4. TFF measurement

The TFF was obtained by adjusting the simulation to the data x spectrum. A χ^2 fit to the reconstructed x distribution of the π^0_D event candidates distributed over equipopulated bins has been performed to extract the TFF slope value. The NA62 preliminary result on the π^0 TFF slope parameter is obtained as:

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

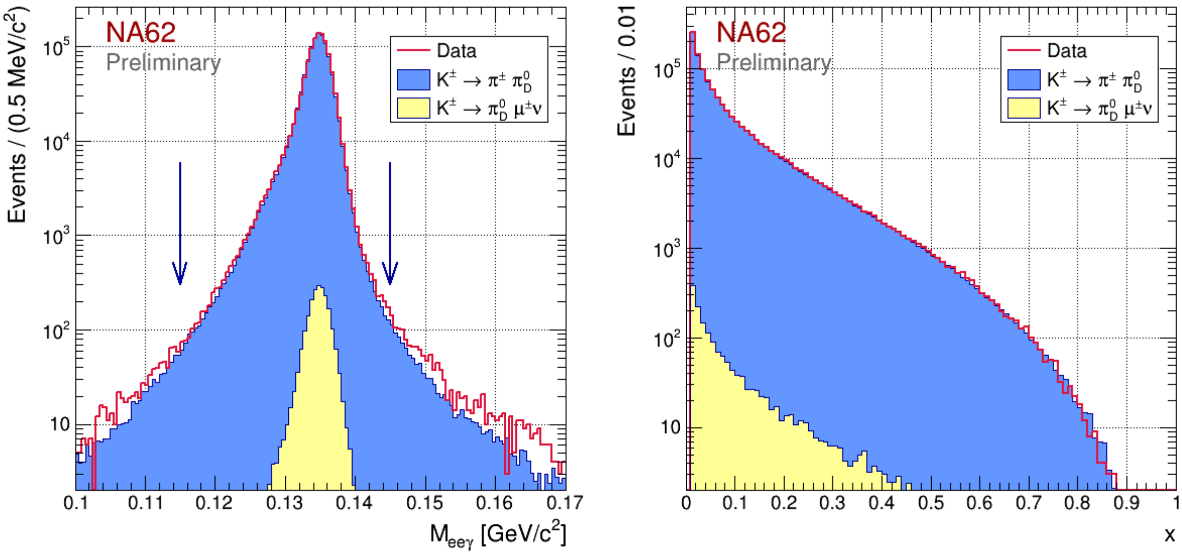


Figure 2. Left: Reconstructed and simulated invariant mass of π^0_D.
Right: Reconstructed x Dalitz variable for data and MC components. The TFF slope parameter value used to generate MC events was $a_{sim} = 0.032$.

The fit result is illustrated in Figure 3 where the effect of a positive TFF slope is clearly seen from the ratio of the data and MC distribution reweighted to a value $a = 0$. The horizontal positions of black markers correspond to the barycenters of the data distributed over 20 equipopulated bins. The red solid line represents the TFF function with the slope value equal to the fit central value. Red dashed lines correspond to the 1 σ band. The breakdown of the uncertainties is presented in Table 1. The value of the slope parameter can be compared to the various TFF theory expectations:

- $a = (2.90 \pm 0.50) \times 10^{-2}$, χPT [7];
- $a = (3.07 \pm 0.06) \times 10^{-2}$, dispersion theory [8];
- $a = (2.92 \pm 0.04) \times 10^{-2}$, two-hadron saturation [9].

The results from other experiments are shown in Figure 3.

5. Search for the dark photon

The idea of a new U(1) gauge symmetry with a very light gauge boson, called a Dark Photon (DP, usually denoted as A' boson) has been proposed in [10], [11]. The DP could mediate the annihilation of Dark Matter particles and explain the excess of positrons in cosmic rays [12] and also explain the muon gyromagnetic ratio $(g-2)$ measurement [13]. Dark photon presence could manifest itself in the NA48/2 data set by the process $\pi^0 \to \gamma A'$ decay followed by the prompt $A' \to e^+e^-$ decay. The signal decay chain has the same particles in the final state as the π^0 Dalitz decay. The DP is characterized by two a priori unknown parameters, the mass $m_{A'}$ and the mixing parameter ε^2. The expected branching fraction of π^0 into the DP is [14]

$$\mathcal{B}(\pi^0 \to \gamma A') = 2\varepsilon^2 \left(1 - \frac{m^2_{A'}}{m^2_{\pi^0}}\right)^3 \mathcal{B}(\pi^0 \to \gamma\gamma), \tag{6}$$

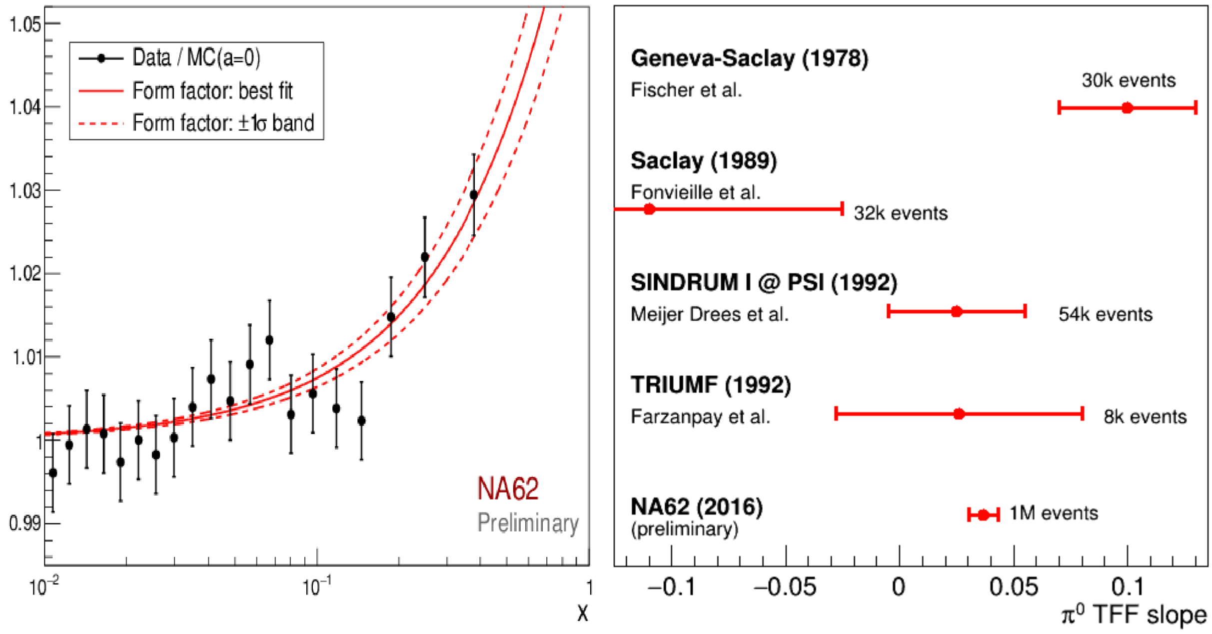


Figure 3. Left: Fit result illustration. Right: Results on the TFF slope from π^0_D measurements.

Table 1. Summary of uncertainty sources.

Source	$\delta a (\times 10^2)$
Statistical-Data	0.49
Statistical-MC	0.20
Beam momentum spectrum simulation	0.30
Spectrometer momentum scale	0.15
Spectrometer resolution	0.05
LKr non-linearity and energy scale	0.04
Particle mis-ID	0.08
Accidental background	0.08
Neglected π^0_D sources in MC	0.01

which is kinematically suppressed as $m_{A'}$ approaches m_{π^0}. In the DP mass range $2m_e < m_{A'} < m_{\pi^0}$ accessible in pion decays, the only allowed tree-level decay into SM fermions is $A' \to e^+e^-$, while the loop-induced SM decays ($A' \to 3\gamma,\ A' \to \nu\bar{\nu}$) are highly suppressed. Therefore, for a DP decaying only into SM particles, $\mathcal{B}(A' \to e^+e^-) \approx 1$, the expected total decay width is [14]

$$\Gamma_{A'} \approx \Gamma(A' \to e^+e^-) = \frac{1}{3}\alpha\varepsilon^2 m_{A'}\sqrt{1-\frac{4m_e^2}{m_{A'}^2}}\left(1+\frac{2m_e^2}{m_{A'}^2}\right). \tag{7}$$

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

$$c\tau_{A'} = hc/\Gamma_{A'} \approx 0.8\mu m \times \left(\frac{10^{-6}}{\varepsilon^2}\right) \times \left(\frac{100\mathrm{MeV}/c^2}{m_{A'}}\right). \tag{8}$$

This analysis is performed assuming that the DP decays at the production point (prompt decay), which is valid for sufficiently large values of $m_{A'}$ and ε^2. Then the DP has the same production and signature as the Dalitz decay $\pi^0_D \to e^+e^-\gamma$, that represents an irreducible but well controlled background.

The result of the analysis of the full data set of NA48/2 including a total of 1.69×10^7 π^0_D reconstructed events is reported. The π^0_D events are coming from kaon decays $\mathrm{K}^\pm \to \pi^\pm\pi^0$ ($\mathrm{K}_{2\pi}$) and $\mathrm{K}^\pm \to \pi^0\mu^\pm\nu$ ($\mathrm{K}_{\mu 3}$), followed by the prompt $\pi^0 \to \gamma A'$, $A \to e^+e^-$ decay chain. These two exclusive selections apply the following criteria:
$\mathrm{K}_{2\pi}$ selection:

- $|m_{\pi\gamma ee} - m_K| < 20$ MeV/c^2;
- $|m_{\gamma ee} - m_{\pi^0}| < 8$ MeV/c^2;
- no missing momentum.

$\mathrm{K}_{\mu 3}$ selection:

- $m^2_{miss} = (P_K - P_\mu - P_{\pi^0})^2$ compatible with 0;
- $|m_{\gamma ee} - m_{\pi^0}| < 8$ MeV/c^2;
- missing total and transverse momentum.

The numbers of reconstructed events from $\mathrm{K}_{2\pi}$ ($\mathrm{K}_{\mu 3}$) are 1.38×10^7 (0.31×10^7), respectively. A search for resonances in the di-electron invariant mass spectrum has been performed in the mass range 9 MeV/$c^2 \leq m_{A'} < 120$ MeV/c^2. The lower boundary of the mass range is determined by the limited accuracy of the π^0_D background simulation at low e^+e^- mass. The obtained upper limits on the numbers of DP candidates and $\mathcal{B}(\pi^0 \to \gamma A')$ in each mass hypothesis considered are presented in Figure 4.

No signal was observed and upper limits on the DP mixing parameter ε^2 were improved in the DP mass range 9 MeV/$c^2 < m_{A'} < 70$ MeV/c^2, see Figure 5. If dark photon couples to quarks and decays mainly to SM fermions, it is ruled out as explanation for the anomalous $(g-2)_\mu$ measurement.

Conclusion

A total of 1.05×10^6 π^0 Dalitz decays, originating from $\mathrm{K}^\pm \to \pi^\pm\pi^0$ decays, have been fully reconstructed. A preliminary measurement of the π^0 transition form factor slope based on NA62 2007 data statistics was performed:

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

The precision of the TFF measurement has been improved in the time-like momentum region. Final result is in preparation.

Improved limits (down to $\epsilon^2 = 2 \times 10^{-7}$) in the 9-70 MeV/$c^2$ mass range of the dark photon search in π^0 decays has been achieved by exploring NA48/2 data. The whole region favored by $(g-2)_\mu$ is excluded, assuming that DP decays into SM fermions only.

Acknowledgments

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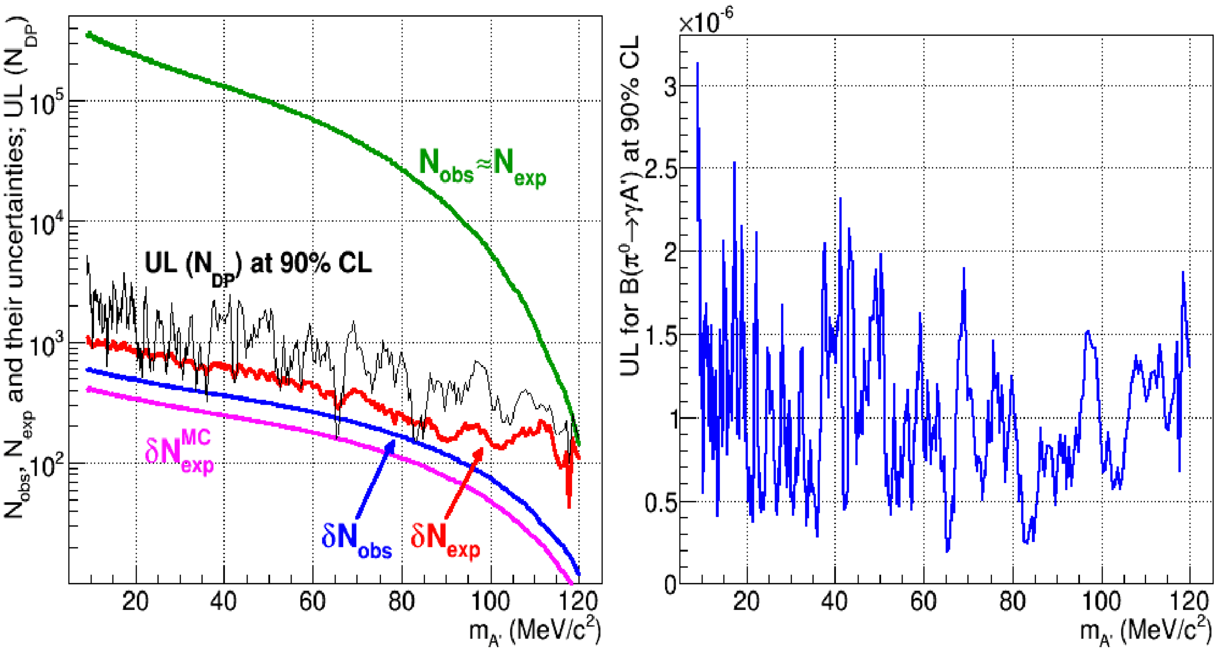

Figure 4. Left: Numbers of observed data events (N_{obs}) and expected π^0_D background events (N_{exp}) passing the joint DP selection (indistinguishable in a logarithmic scale), estimated uncertainties $\delta N_{obs} = \delta N_{exp}$ and δN_{exp}, and obtained upper limits at 90% CL on the numbers of DP candidates (N_{DP}) for each DP mass vale $m_{A'}$. The contribution to δN_{exp} from the MC statistical uncertainty is shown separately (δN^{MC}_{exp}). The remaining and dominant component is due to the statistical errors on the trigger efficiencies measured in the DP signal region. Right: Obtained upper limits on $\mathcal{B}(\pi^0 \rightarrow \gamma A')$ at 90% CL for each DP mass value $m_{A'}$.

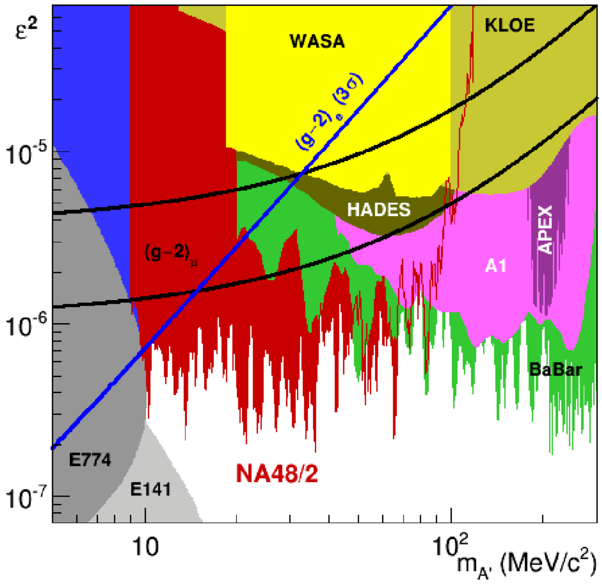

Figure 5. Upper limits at 90% CL on the mixing parameter ε^2 versus the DP mass $m_{A'}$ obtained from $\pi^0 \rightarrow \gamma A'$ search by NA48/2, compared to other published exclusion limits from meson decay, beam dump and e^+e^- collider experiments.Further details can be found in [15].

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