Search for the Dark Photon in $\pi^0$ Decays by NA48/2 at CERN

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on behalf of the NA48/2 collaboration

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CERN NA48/NA62 Experiments

Kaon decay in flight experiments.
NA48/2: ~120 participants, 15 institutions
NA62: ~200 participants, 30 institutions

2014: pilot run
2015: 1st K⁺→π⁺νν run

Earlier: NA31
1997: $\varepsilon'/\varepsilon$: $K_L+K_S$
1998: $K_L+K_S$
1999: $K_L+K_S$ K₅ HI
2000: $K_L$ only K₅ HI
2001: $K_L+K_S$ K₅ HI
2002: $K_S$/hyperons
2003: $K^+/K^-$
2004: $K^+/K^-$ tests
2007: $K^\pm_{e2}/K^\pm_{\mu2}$ tests
2008: $K^\pm_{e2}/K^\pm_{\mu2}$

NA48/1: NA48/2
NA62
Rₓ phase

Jura mountains
Geneva airport

SPS
NA48/NA62: centre of the LHC

France
LHC

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Principal subdetectors:

- Magnetic spectrometer (4 DCHs)
  \[ \frac{\delta p}{p} = (1.02 \oplus 0.044p)\% \quad [p \text{ in GeV/c}] \]

- Scintillator hodoscope (HOD)
  Low-level trigger, time measurement (150ps).

- Liquid Krypton EM calorimeter (LKr)
  High granularity, quasi-homogeneous;
  \[ \frac{\sigma_E}{E} = (3.2/E^{1/2} \oplus 9/E \oplus 0.42)\% \quad [E \text{ in GeV}] \]
  \[ \sigma_x = \sigma_y = (4.2/E^{1/2} \oplus 0.6)\text{mm} \quad (1.5\text{mm@10GeV}) \]
The Dark Photon


The simplest hidden sector model introduces an extra \( \mathbf{U}(1) \) gauge symmetry with its gauge boson: the dark photon \( (A') \).

QED-like interaction with SM fermions:

\[
\mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu
\]

Coupling constant and charges can be generated through kinetic mixing between the QED and the new \( \mathbf{U}(1) \) gauge bosons

\[
\mathcal{L}_{mix} = -\frac{\epsilon}{2} F_{\mu \nu}^{QED} F_{\mu \nu}^{dark}
\]

Motivations:

1) Possible explanation for positron (but not antiproton) excess in cosmic rays (PAMELA, FERMI, AMS-02) by dark matter annihilation.

2) Possible solution for the muon \( g-2 \) anomaly.
DP Production in $\pi^0 \rightarrow \gamma A'$ Decay

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

Batell, Pospelov and Ritz, PRD80 (2009) 095024

- Two unknown parameters: mass ($m_{A'}$) and mixing ($\varepsilon^2$).
- Sensitivity to DP for $m_{A'} < m_{\pi^0}$.
- Loss of sensitivity to $\varepsilon^2$ as $m_{A'}$ approaches $m_{\pi^0}$, due to kinematical suppression of the $\pi^0 \rightarrow \gamma A'$ decay.

$\text{BR}(\pi^0 \rightarrow \gamma A') / \varepsilon^2$ vs $m_{A'}$

valid for $\varepsilon^2 \ll 1$
DP Decays into SM Fermions

Batell, Pospelov and Ritz, PRD80 (2009) 095024

Accessible in $\pi^0$ decays: assuming decays only into SM fermions,

$$\Gamma_{A'} \approx \Gamma(A' \rightarrow e^+e^-) = \frac{1}{3} \alpha \varepsilon^2 m_{A'} \sqrt{1 - \frac{4m_e^2}{m_{A'}^2}} \left(1 + \frac{2m_e^2}{m_{A'}^2}\right) \approx \alpha \varepsilon^2 m_{A'}/3$$
DP proper lifetime below the di-muon threshold:

\[ c\tau_{A'} \approx 0.8 \mu m \times \left( \frac{10^{-6}}{\varepsilon^2} \right) \times \left( \frac{100 \text{ MeV}}{m_{A'}} \right) \]

Mean free path at \( E_{A'}=50 \text{ GeV} \) (maximum energy at NA48/2):

\[ L_{\text{max}} \approx 0.4 \text{ mm} \times \left( \frac{10^{-6}}{\varepsilon^2} \right) \times \left( \frac{100 \text{ MeV}}{m_{A'}} \right)^2 \]

- For \( \varepsilon^2>10^{-7} \) and \( m_{A'}>10 \text{ MeV}/c^2 \), DP path length is negligible with respect to the resolution on the vertex longitudinal coordinate (\( \sim 1 \text{ m} \)).
- Therefore prompt DP decay is assumed.
- DP production and decay signature (\( \pi^0 \rightarrow \gamma A', A' \rightarrow e^+e^- \)) is identical to that of \( \pi^0_D \rightarrow \gamma e^+e^- \) decay.
NA48/2 Data Sample

- NA48/2 data: $\sim 2 \times 10^{11} K^\pm$ decays in the fiducial decay region.
  - Production and decay in vacuum of $\sim 5 \times 10^{10}$ tagged boosted $\pi^0$ mesons.
  - Mean free path of the $\pi^0$ is negligible (few $\mu$m).
  - Sources of $\pi^0$ mesons considered: $K^\pm \to \pi^\pm \pi^0$ decay ($\text{BR}=20.7\%$) and $K^\pm \to \pi^0 \mu^\pm \nu$ decay ($\text{BR}=3.4\%$).

- Search for the prompt $\pi^0 \to \gamma A'$, $A' \to e^+ e^-$ decay chain.
  - Identical signature to $K^\pm \to \pi^\pm \pi^0_D$ and $K^\pm \to \pi^0_D \mu^\pm \nu$ decays, three-track vertex topology.
  - Sensitivity determined by irreducible $\pi^0_D \to \gamma e^+ e^-$ background ($\text{BR}=1.2\%$).
  - Efficient trigger chain for 3-track vertices throughout the data taking based on HOD multiplicity ($L1$) and DCH track reconstruction ($L2$).
  - Search for a narrow peak in $e^+ e^-$ invariant mass spectrum.
  - Excellent $e^+ e^-$ mass resolution: $\sigma_m \approx 0.011 m_{ee}$.

- Acceptance for both $K^\pm \to \pi^\pm \pi^0$ and $K^\pm \to \pi^0 \mu^\pm \nu$ signal chains: depending on $m_{A'}$, up to $4.5\%$. 

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The $\pi^0_D$ Sample

Two exclusive selections

$K^\pm \to \pi^\pm \pi^0_D$ selection:
- $|m_{\gamma ee} - m_K| < 20 \text{ MeV}/c^2$;
- $|m_{\gamma ee} - m_{\pi^0}| < 8 \text{ MeV}/c^2$;
- no missing momentum.

$K^\pm \to \pi^0_D \mu^\pm \nu$ selection:
- $m_{\text{miss}}^2 = (P_K - P_\mu - P_{\pi^0})^2$ compatible with zero;
- $|m_{\gamma ee} - m_{\pi^0}| < 8 \text{ MeV}/c^2$;
- missing total and transverse momentum.

Reconstructed $\pi^0_D$ decay candidates:
- $N(K_{2\pi D}) = 1.38 \times 10^7$,
- $N(K_{\mu 3D}) = 0.31 \times 10^7$,
- total = $1.69 \times 10^7$.

$K^\pm$ decays in fiducial region $N_K = (1.57 \pm 0.05) \times 10^{11}$.

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Simulation of $\pi^0_D$ Background

Kinematic variables:

$$x = \frac{(Q_1 + Q_2)^2}{m^2_{\pi^0}} = \left(\frac{m_{ee}}{m_{\pi^0}}\right)^2, \quad y = \frac{2P(Q_1 - Q_2)}{m^2_{\pi^0}(1 - x)}$$

Differential decay rate (lowest order):

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

$r = 2m_e/m_\pi$

Radiative corrections:

$$\frac{d\Gamma}{dx dy} = \delta(x, y) \frac{d\Gamma^0}{dx dy}$$

Limitation: no emission of real photons.

Mikaelian and Smith, PRD5 (1972) 1763
Husek, Kampf and Novotný, arXiv:1504.06178

$\pi^0$ transition form-factor: $F(x)=1+ax$.

- Theory expectation for the TFF slope:
  $$a=0.0307\pm0.0006 \ [Hoferichter et al., 2014]$$
  or the PDG average $$a=0.032\pm0.004 \ [PDG 2014]$$
  cannot be used due to limited precision on the radiative corrections to $\pi^0_D$.
- An effective TFF slope value is obtained from the $\pi^0_D$ data sample itself.
Search for DP Signal

DP signal: a narrow peak in the $m_{ee}$ spectrum of $\pi^0_D$ candidates

- DP mass scan performed:
  - range: $9 \text{ MeV/c}^2 \leq m_{A'} < 120 \text{ MeV/c}^2$;
  - at lower $m_{A'}$, background acceptance simulation has limited precision;
  - variable DP mass step: $\approx 0.5\sigma_m$;
  - signal mass window optimized to maximize expected sensitivity: $\pm 1.5\sigma_m$;
  - DP mass hypotheses tested: 404.

- For each $m_{A'}$, frequentist confidence intervals for $N_{DP}$ obtained from numbers of observed and expected events ($N_{obs}$, $N_{exp}$) and their uncertainties.

- Local signal significance never exceeds $3\sigma$: no DP signal is observed.
Acceptances of the DP selection for $K^\pm \rightarrow \pi^\pm \pi^0$, $K^\pm \rightarrow \pi^0 \mu^\pm \nu$ and $K^\pm \rightarrow \pi^\pm \pi^0 \pi^0$ decays followed by the prompt $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$ decay chain.

- Weak $m_{A'}$ dependence: cancellation of $m_{A'}$ dependencies of background fluctuation and acceptance.
- The obtained limits are background-limited (2–3 orders of magnitude above single event sensitivity).
DP Exclusion summary

- Improvement on the existing limits in the $m_{A'}$ range $9-70$ MeV/c$^2$.
- Most stringent limits are at low $m_{A'}$ (kinematic suppression is weak).
- Sensitivity limited by the irreducible $\pi_0^D$ background, ULs are 2–3 orders of magnitude above SES.
- Upper limit on $\varepsilon^2$ scales as $\sim(1/N_K)^{1/2}$: modest improvement with larger samples.
- If DP couples to quarks and decays mainly to SM fermions, it is ruled out as the explanation for the anomalous $(g-2)_\mu$. 

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Comparison of ($K^\pm \rightarrow \pi^\pm A'$, $A' \rightarrow e^+e^-$, $m_{A'} > m_{\pi^0}$) vs ($\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$, $m_{A'} < m_{\pi^0}$):

- Lower irreducible background: $BR(K^\pm \rightarrow \pi^\pm e^+e^-) \sim 10^{-7}$ vs $BR(\pi^0_D) \sim 10^{-2}$.
- Higher acceptance ($\times 4$), favourable $K/\pi^0$ flux ratio ($\times 4$).
- Therefore the expected BR limits: $BR(K^\pm \rightarrow \pi^\pm A') \sim 10^{-9}$ vs $BR(\pi^0 \rightarrow \gamma A') \sim 10^{-6}$.
- However $BR(K^\pm \rightarrow \pi^\pm A')/BR(\pi^0 \rightarrow \gamma A') \sim 10^{-4}$, expected $\epsilon^2$ limits are $\epsilon^2 \sim 10^{-5}$.
New NA48/2 result on dark photon search in $\pi^0$ decays:


- Integrated kaon flux analysed: $1.7 \times 10^{11}$ decays in flight.
- Assumption: DP decays into SM fermions only.
- Improved limits on DP mixing $\varepsilon^2$ in the 9–70 MeV/c$^2$ mass range.
- The strongest limits ($\varepsilon^2 \sim 2 \times 10^{-7}$) are at $\sim 10$ MeV/c$^2$ mass.
- The whole region favoured by $(g-2)_\mu$ is excluded now.
- Background-limited measurement: hard to improve below $\varepsilon^2 = 10^{-7}$.
- Search via $K^{\pm} \rightarrow \pi^{\pm} A'$ ($m_{\pi^0} < m_{A'} < m_K - m_{\pi}$) is not competitive.

Possible further directions:

- Larger $\pi^0$ decay sample from $K^+$ decays and improved resolution at NA62.
- Studies of invisible $A'$ decays at NA62 ($K^+ \rightarrow \pi^+ +$ nothing).
- Probing lower $\varepsilon^2$: sensitivity studies for $\pi^0 \rightarrow \gamma A'$ with a displaced $A' \rightarrow e^+e^-$ vertex.