Search for the dark photon at NA48 and NA62

Francesco Gonnella on behalf of the NA62 collaboration

26 September 2015

Phi Psi 2015 – USTC Hefei, AnHui - China
The simplest hidden sector model introduces an extra $U(1)$ 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 $U(1)$ 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.
Simultaneous coaxial narrow momentum band K± beams: P_K = 60 GeV/c, \( \delta P_K/P_K \approx 3\% \) (rms).

Rate of K± decays: \( \sim 100 \) kHz.

Data taking: six months in 2003-04.

Main trigger: 3-track vertex.

Principal sub-detectors:

- **Magnetic spectrometer (4 DCHs)**
  - 4 views/DCH: redundancy. Level2 trigger.
  - \( \delta p/p = (1.02 \pm 0.044p)\% \) [p in GeV/c]

- **Scintillator hodoscope (HOD)**
  - Level1 trigger, time measurement (150ps)

- **Liquid Krypton EM calorimeter (LKr)**
  - High granularity, quasi-homogeneous;
  - \( \sigma_E/E = (3.2/E^{1/2} \pm 9/E \pm 0.42)\% \) [E in GeV]
  - \( \sigma_x = \sigma_y = (4.2/E^{1/2} \pm 0.6)\text{mm} \) (1.5mm@10GeV)
Dark-photon decays into SM particles

Batell, Pospelov and Ritz, PRD80 (2009) 095024

\[ \Gamma_{A'} \approx \Gamma(A' \rightarrow e^+ e^-) = \frac{1}{3} \alpha \varepsilon^2 m_{A'} \sqrt{1 - \frac{4m_e^2}{m_{A'}^2}} \left(1 + \frac{2m_e^2}{m_{A'}^2}\right) \approx \alpha \varepsilon^2 m_{A'}/3 \]
Dark-photon production in $\pi^0$ decays

Batell, Pospelov and Ritz, PRD80 (2009) 095024

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

- 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.
Dark-Photon lifetime and mean path

Dark-photon 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 \( \pi^0 \rightarrow \gamma e^+e^- \) decay.

DP mean path vs \( m_{A'} \)

Assuming \( \varepsilon^2=10^{-6} \)

Mean path at \( E=20 \, \text{GeV} \)

Proper time
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
  - Sources: \( K^\pm \rightarrow \pi^\pm \pi^0 \) decay (BR=20.7%) and \( K^\pm \rightarrow \pi^0 \mu^\pm \nu \) decay (BR=3.4%)
  - Mean free path of the \( \pi^0 \) is negligible (few \( \mu m \))
  - Efficient trigger chain for 3-track vertices throughout the data-taking based on HOD multiplicity (L1) and DCH track reconstruction (L2)

- **Search for the prompt** \( \pi^0 \rightarrow \gamma A', A' \rightarrow e^+ e^- \) decay chain
  - Identical signature to \( K^\pm \rightarrow \pi^\pm \pi^0_D \) and \( K^\pm \rightarrow \pi^0_D \mu^\pm \nu \) decays, three-track vertex topology.
  - Sensitivity determined by irreducible \( \pi^0_D \rightarrow \gamma e^+ e^- \) background (BR=1.2%)
  - Search for a **narrow peak** in \( e^+ e^- \) invariant mass spectrum
  - Excellent \( e^+ e^- \) mass resolution: \( \sigma_m \approx 0.011 \times m_{ee} \).

- **Acceptance for both** \( K^\pm \rightarrow \pi^\pm \pi^0 \) and \( K^\pm \rightarrow \pi^0 \mu^\pm \nu \) signal chains: depending on \( m_{A'} \), up to 4.5%
Two exclusive selections

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

\( K^{\pm} \rightarrow \pi^0_D \mu^{\pm} \nu \) selection:
- \( m_{\text{miss}}^2 = (P_K - P_{\mu} - P_{\pi^0})^2 \) compatible with zero
- \( |m_{\gamma ee} - m_{\pi^0}| < 8 \text{ MeV}/c^2 \)
- no 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:
\( N_K = (1.57 \pm 0.05) \times 10^{11} \)
Dark-photon signal is a narrow peak in the $m_{ee}$ distribution of $\pi^0_D$ decays

- **DP mass scan performed:**
  - range: 9 MeV/c² ≤ $m_\Delta'$ < 120 MeV/c²
  - variable DP mass step: $\approx 0.5\sigma_m$
  - signal mass-window optimised to maximise expected sensitivity: $\pm 1.5\sigma_m$
  - DP-mass hypotheses tested: 404

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

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

Weak $m_{A'}$ dependence: cancellation of $m_{A'}$ dependencies of background fluctuation and acceptance.
 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 $(g-2)_{\mu}$.
The NA62 experiment
Ultra rare kaon-decays

\( K^+ \to \pi^+ \nu \bar{\nu} \): theoretically pure and almost experimentally unexplored

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Ratio ( \times 10^{11} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^+ \to \pi^+ \nu \bar{\nu} )</td>
<td>Theory (SM)</td>
</tr>
<tr>
<td>( K^0 \to \pi^0 \nu \bar{\nu} )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Theory (SM)</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^+ \to \pi^+ \nu \bar{\nu} )</td>
<td>9.11 ( \pm 0.72 ) [1]</td>
<td>17.3 ( +11.5 -10.5 ) [2]</td>
</tr>
<tr>
<td>( K^0 \to \pi^0 \nu \bar{\nu} )</td>
<td>3.00 ( \pm 0.30 ) [1]</td>
<td>(&lt;2600 (90% CL) ) [3]</td>
</tr>
</tbody>
</table>

NA62 goal is to measure this BR to 10% precision

in addition: \( |V_{td}| \) to \( \leq 10\% \) accuracy

These processes are very sensitive probes for new physics:

- They are highly suppressed
- They are predicted with very high accuracy

In-flight kaon decay at 75 GeV/c

- Large missing momentum

**Kinematic Signature**

- \( P_k = 75 \text{ GeV} \), \( \pi^+ \)
- \( P_k = 75 \text{ GeV}/c \)
- \( \gamma \gamma \) High Energy

**Cuts on the missing mass**

\[
m^2_{\text{miss}} = (P_k - P_\pi)^2
\]

defines 2 regions where the signal is not dominated by background

- Neutrinos carry \( \geq 40 \text{ GeV}/c \) momentum
- Require: \( P_\pi = 15 - 35 \text{ GeV}/c \)

Rejects \( \approx 92\% \) of Kaon decays
NA62 detector layout and principles

- High-performance EM calorimeter
- High-rate, precision tracking
- Redundant particle ID e/μ/π
- Hermetic photon vetoes

KTAG
- Differential Cerenkov for K⁺ ID in beam
- Beam tracking Si pixels, 3 stations

CHANTI
- Charged veto

GIGATRACKER

LAV
- Large-angle photon vetoes
- OPAL lead glass

RICH
- RICH μ/π ID
- 1 atm Ne

MUV
- μ veto
- Fe/scint

Dipole spectrometer
- 4 straw-tracker stations

Fiducial volume ~60m
- 10⁻⁶ mbar

5 MHz K⁺ decays

γ veto

IRC

γ veto

SAC

Forward γ veto

GIGA

High-performance EM calorimeter

High-rate, precision tracking

Redundant particle ID e/μ/π

Hermetic photon vetoes
NA62 prospects for the $K^{\pm} \rightarrow \pi^{\pm} A'$ decay

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: $\text{BR}(K^{\pm} \rightarrow \pi^{\pm} e^+e^-) \sim 10^{-7}$ vs $\text{BR}(\pi^0_D) \sim 10^{-2}$.
- Higher acceptance ($\times 4$), favourable $K/\pi^0$ flux ratio ($\times 4$).
- Therefore the expected BR limits: $\text{BR}(K^{\pm} \rightarrow \pi^{\pm} A') \sim 10^{-9}$ vs $\text{BR}(\pi^0 \rightarrow \gamma A') \sim 10^{-6}$.
- However $\text{BR}(K^{\pm} \rightarrow \pi^{\pm} A')/\text{BR}(\pi^0 \rightarrow \gamma A') \sim 10^{-4}$, expected $\varepsilon^2$ limits are $\varepsilon^2 \sim 10^{-5}$. 

---

Dark photon emission BRs/\varepsilon^2

\[ \pi^0 \rightarrow \gamma A' (\times 10^{-4}) \]

Davoudiasl, Lee, Marciano

PRD89 (2014) 095006

Expected ULs for BR and $\varepsilon^2$

Complementary $m_{A'}$ interval to $\pi^0$ decays ...

$\text{BR}(K^+ \rightarrow \pi^+ A') \times 10^4$

$\sim 10^{-9}$

$\varepsilon^2 \sim 10^{-5}$

... but not competitive to existing limits
### Further NA62 K-physics programme

<table>
<thead>
<tr>
<th>$K^+$ decay</th>
<th>Physics</th>
<th>Present limit (90% C.L.) / Result</th>
<th>NA62</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+\mu^+e^-$</td>
<td>LFV</td>
<td>$1.3 \times 10^{-11}$</td>
<td>$0.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\pi^+\mu^-e^+$</td>
<td>LFV</td>
<td>$5.2 \times 10^{-10}$</td>
<td>$0.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\pi^-\mu^+e^+$</td>
<td>LNV</td>
<td>$5.0 \times 10^{-10}$</td>
<td>$0.7 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\pi^-e^+e^+$</td>
<td>LNV</td>
<td>$6.4 \times 10^{-10}$</td>
<td>$2 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\pi^-\mu^+\mu^+$</td>
<td>LNV</td>
<td>$1.1 \times 10^{-9}$</td>
<td>$0.4 \times 10^{-12}$</td>
</tr>
<tr>
<td>$\mu^-\nu e^+e^+$</td>
<td>LNV/LFV</td>
<td>$2.0 \times 10^{-8}$</td>
<td>$4 \times 10^{-12}$</td>
</tr>
<tr>
<td>$e^-\nu\mu^+\mu^+$</td>
<td>LNV</td>
<td>No data</td>
<td>$10^{-12}$</td>
</tr>
</tbody>
</table>

| $\pi^+X^0$ | New Particle | $5.9 \times 10^{-11}$ m$_{X^0} = 0$ | $10^{-12}$ |
| $\pi^+\chi\chi$ | New Particle | – | $10^{-12}$ |
| $\pi^+\pi^+e^-\nu$ | $\Delta S \neq \Delta Q$ | $1.2 \times 10^{-8}$ | $10^{-11}$ |
| $\pi^+\pi^+\mu^-\nu$ | $\Delta S \neq \Delta Q$ | $3.0 \times 10^{-6}$ | $10^{-11}$ |
| $\pi^+\gamma$ | Angular Mom. | $2.3 \times 10^{-9}$ | $10^{-12}$ |
| $\mu^+\nu_h, \nu_h \rightarrow \nu \gamma$ | Heavy neutrino | Limits up to m$_{\nu_h} = 350$ MeV | |

- $R_K$ | LU | $(2.488 \pm 0.010) \times 10^{-5}$ | $\gg 2$ better |
- $\pi^+\gamma\gamma$ | $\chi$PT | $< 500$ events | $10^5$ events |
- $\pi^0\pi^0e^+\nu$ | $\chi$PT | 66000 events | O(10$^6$) |
- $\pi^0\pi^0\mu^+\nu$ | $\chi$PT | – | O(10$^5$) |
Outlook and conclusion

- New NA48/2 result on dark photon search in $\pi^0$ decays: *Phys.Lett. B746 (2015) 178*
  - 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 in NA62 presently in data-taking:
  - Larger $\pi^0$ decay sample from $K^+$ decays and improved resolution at NA62.
  - Studies of invisible $A'$ decays at NA62 ($K^+ \rightarrow \pi^+ + \text{nothing}$).
  - Probing lower $\varepsilon^2$: sensitivity studies for $\pi^0 \rightarrow \gamma A'$ with a displaced $A' \rightarrow e^+e^-$ vertex.
  - Extended LFV and K-physics programme
Thank you for your attention

francesco.gonnella@lnf.infn.it
Lepton flavour violation in K decays

- Copious production: high statistics
- Simple decay topologies: clean experimental signatures
- High NP mass scales accessible for tree-level contributions:
  - $m_X \sim 100$ TeV

<table>
<thead>
<tr>
<th>Mode</th>
<th>UL at 90% CL</th>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+\mu^+e^-$</td>
<td>$1.3 \times 10^{-11}$</td>
<td>BNL E777/E865</td>
<td>PRD 72 (2005) 012005</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\mu^-e^+$</td>
<td>$5.2 \times 10^{-10}$</td>
<td>BNL E865</td>
<td>PRL 85 (2000) 2877</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^-\mu^+e^+$</td>
<td>$5.0 \times 10^{-10}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^-e^+e^+$</td>
<td>$6.4 \times 10^{-10}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^\mp\mu^\pm\mu^\pm$</td>
<td>$1.1 \times 10^{-9}$</td>
<td>CERN NA48/2</td>
<td>PLB 697 (2011) 107</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^-\nu e^+e^+$</td>
<td>$2.0 \times 10^{-8}$</td>
<td>Geneva-Saclay</td>
<td>PL 62B (1976) 485</td>
</tr>
<tr>
<td>$K^+ \rightarrow e^-\nu\mu^+\mu^+$</td>
<td>no data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \mu^+e^-$</td>
<td>$3.6 \times 10^{-10}$</td>
<td>FNAL KTeV</td>
<td>PRL 100 (2008) 131803</td>
</tr>
<tr>
<td>$\pi^0 \rightarrow \mu^-e^+$</td>
<td>$3.6 \times 10^{-10}$</td>
<td></td>
<td>($K_L$ searches also report)</td>
</tr>
</tbody>
</table>

- Expected NA62 single event sensitivities: $\sim 10^{-12}$ for $K^\pm$ decays
- NA62 is capable of improving on all these decay modes
Simulation of $\pi_0^D$ background

Kinematic variables:

$$x = \frac{(Q_1 + Q_2)^2}{m_{\pi_0}^2} = \left(\frac{m_{ee}}{m_{\pi_0}}\right)^2, \quad y = \frac{2P(Q_1 - Q_2)}{m_{\pi_0}^2(1 - x)}$$

Differential decay rate (lowest order):

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

$\text{(r=2m_e/m_\pi)}$

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: $a = 0.0307 \pm 0.0006$ [Hoferichter et al., 2014]
  or the PDG average $a = 0.032 \pm 0.004$ [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.
NA62 beam line

<table>
<thead>
<tr>
<th>Beam Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>400 GeV/c Protons on Target / s</td>
<td>$1.1 \times 10^{12}$</td>
</tr>
<tr>
<td>75 GeV/c Hadrons / s</td>
<td>$750 \times 10^6$</td>
</tr>
<tr>
<td>$K^+$ decays / s</td>
<td>$4.5 \times 10^6$</td>
</tr>
<tr>
<td>$K^+$ decays / y</td>
<td>$4.5 \times 10^{12}$</td>
</tr>
<tr>
<td>Beam composition</td>
<td>p 70% π 24% K 6%</td>
</tr>
</tbody>
</table>

- NA62 uses SPS 400 GeV/c proton beam
- Proton beam interacts with a Beryllium target
- Among the interaction products, 75 GeV/c $K^+$ are selected
- Nonetheless kaons, are a minimal part of the beam (45 MHz / 750 MHz)