Search for the dark photon at NA48/2 and NA62

Mauro Raggi, Sapienza Università di Roma e INFN Roma
On behalf of the NA48/2 and NA62 collaborations

Light Dark Matter @ Accelerators La Biodola 24-28 Maggio 2017
What is the universe made of?

- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interacts gravitationally

- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?
The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the “dark photon" or $A'$ boson.

The coupling constant and the charges can be generated effectively through the kinetic mixing between the QED and the new U(1) gauge bosons:

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

- In this *case the new coupling constant* $= e \epsilon$ is just proportional to electric charge and it is equal for both quarks and leptons.

As in QED, this will generate new interactions with SM fermions of type:

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

- Not all the SM particles need to be charged under this new symmetry
- In the *most general case* $q_f$ is different in between leptons and quarks and can even be 0 for quarks. *P. Fayet, Phys. Lett. B* 675, 267 (2009)
Dark photon and g-2\(_\mu\)

About 3\(s\) discrepancy between theory and experiment. Could be due to hadronic uncertainties on the Light by Light scattering?

**g-2 and A’**

Additional diagram with dark photon exchange can fix the discrepancy! (with sub GeV A’ masses 😊)

**M. Pospelov**  
Dark photon searches status 2015

- Visible decays: $A' \rightarrow ee, \mu\mu, \pi\pi$
  - Kinetic mixed dark photons simplest model

- Favored parameters values explaining muon $g-2$ (green band)
  - $A'$-boson light 10-100 MeV

- Status of dark photon searches
  - Beam dump experiments (grey)
  - Fixed target (Apex, A1)
  - Mesons decays (Babar, KLOE, Wasa)

- Theoretical exclusion from $g_e-2, g_{\mu}-2$
  - Tight limit form $\alpha_{EM}$ (red filled area) PhysRevD.86.095029

- Much less constraints on “Invisible” decay mode
  - If $M_\chi < M_{A'}/2$, $A' \rightarrow \chi\chi$, $\varepsilon^2$ suppression to all visible modes
  - No assumption on $\alpha_D$ and no kinetic mixing
The NA48/2 and NA62 experiments @ SPS

NA48/2 collaboration: 15 institutes from 8 countries:
NA62 collaboration: 29 institutes from 13 countries
**NA48/2 (2003-04)**

**NA48/2 data taking**: 4 months in 2003-04 (K±) 60 GeV Simultaneous K± beam

**Magnetic Spectrometer**
- 4 drift chambers and a dipole magnet

\[
\frac{\sigma(p)}{p} = (1.02 \pm 0.044 p)\% \quad p \text{ in GeV/c}
\]

**Liquid Krypton EM calorimeter (LKr)**
- High granularity (13248 cells of 2x2 cm²)
- Quasi-homogeneous, 7m³ liquid Kr (27X₀)

\[
\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.4\% \quad E \text{ in GeV}
\]

\[
K^\pm \rightarrow \pi^\pm \pi^0 \quad \pi^0 \rightarrow \gamma A' \quad A' \rightarrow e^+e^-; \quad \text{PLB 746 (2015) 178}
\]

\[
K^\pm \rightarrow \pi^\pm A' \quad A' \rightarrow \ell^+\ell^-; \quad \text{PLB 769 (2017) 67–76}
\]
Search for dark photons at NA62

- NA62 has an high intensity hadron beam and can search for A' using different experimental techniques and production mechanisms
  - Meson decay and proton bremsstrahlung: dedicated dump mode
    - Dedicated talk by M. Mirra
  - Mesons decay (K and pions): parasitic to πνν searches
    - $K^+ \rightarrow \pi^+\pi^0 \quad \pi^0 \rightarrow \gamma A' \quad A' \rightarrow \chi\chi$ A’ invisible decays.
    - $K^+ \rightarrow \pi^+A'$ with $A' \rightarrow \chi\chi$ or $A' \rightarrow \ell^+\ell^-$ invisible and invisible

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Dark photon in $\pi^0$ decays
Dark photon in $\pi^0$ decays

Production (kinetic mixing)

Decay (if no light dark sector)

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

$BR(\pi^0 \rightarrow \gamma A') / BR(\pi^0 \rightarrow \gamma \gamma) \approx 2\varepsilon^2 |F(M_{A'}^2)|^2 \left(1 - \frac{M_{A'}^2}{M_{\pi}^2}\right)^3$

valid for $\varepsilon^2 \ll 1$

$M_{A'} < M_{\pi^0}$ and no lighter wrt $A'$
dark sector particles exist $BR(A' \rightarrow e^+ e^-) = 1$

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Number of kaon decays in NA48/2 ('03/'04): \( N_K \approx 2 \cdot 10^{11} \)
- 5 \( \cdot 10^{10} \) \( \pi^0 \) tagged decays from \( K^\pm \rightarrow \pi^\pm \pi^0 \) and \( K^\pm \rightarrow \pi^0 \mu^+\nu \) decays

Exclusive search for the decay chain \( \pi^0 \rightarrow \gamma A', A' \rightarrow e^+e^- \)
- Search for a narrow peak in the \( e^+e^- \) invariant mass.
- High efficiency trigger chain for 3-track vertices throughout all the data taking
- Very good spectrometer mass resolution: \( \sigma_{M_{ee}} \approx 0.012 \times M_{ee} \)

DP final state \( \pi^0 \rightarrow \gamma A', A' \rightarrow e^+e^- \) identical to \( \pi^0_D \rightarrow \gamma e^+e^- \);
- Main background is \( K^\pm \rightarrow \pi^\pm \pi^0_D \) : \( \text{BR}(K_{2pD}) = 2.4 \cdot 10^{-3} \)
- Sensitivity is limited by the irreducible \( K_{2pD} \) background.

Signal acceptance:
- depending on \( M_{A'} \) from 4.5% down to 0.5% for high values \( M_{A'} \).

A total of \(~1.7 \times 10^7\) candidates collected during 2003-04 data taking
Data sample: $K_{2\pi D} + K_{\mu3D}$ selection

- $K^\pm\rightarrow\pi^\pm\pi^0_D$ selection
  - $|M_{ee\gamma} - M_{\pi^0}| < 8$ MeV/c$^2$
  - $|M_{\pi\pi\gamma} - M_K| < 20$ MeV/c$^2$
  - No missing $P_T$: $< 5 \cdot 10^{-4}$ GeV$^2$/c$^2$

- $K^\pm\rightarrow\mu^\pm\pi^0_D$ selection
  - $|M_{ee\gamma} - M_{\pi^0}| < 8$ MeV/c$^2$
  - $M^2_{miss} < 0.01$ GeV$^2$/c$^4$
  - missing $P_T$ due to neutrino: $5 \cdot 10^{-4} < P_T < 0.04$ GeV$^2$/c$^2$
Statistical significance

Scanned DP mass range: $9 \text{ MeV}/c^2 < M_{DP} < 120 \text{ MeV}/c^2.$

- Variable DP mass step: $\pm 1.5\sigma(M_{A'})$.
- DP search window: $\pm 0.5\sigma(M_{A'})$
- 404 DP mass hypothesis tested

Confidence intervals for $N_{A'}$ are computed from:

- $N_{exp}, N_{obs}$ and $\delta N_{obs}, \delta N_{exp}$ in the signal mass window
- Frequentist confidence intervals Rolke-Lopez method.

Local significance never exceeds $3\sigma$: no dark Photon signal observed
Improvement of the existing limits in the range $9-70 \text{ MeV/c}^2$.

If DP couples to SM through kinetic mixing and decays only to SM fermions, it is ruled out as the explanation for anomalous $(g-2)\mu$.

Sensitivity limited by irreducible $\pi^0_D$ background: upper limit on $\varepsilon^2$ scales as $\sim(1/N_K)^{1/2}$, modest improvement with larger data samples.
Impact of NA48/2 measurement

Favored region $(g-2)_\mu$ still available in the low mass region.
Impact of NA48/2 measurement

Favored region \((g-2)\mu\) completely excluded by NA48/2 measurement!

Final result: **PLB746 (2015) 178**
Search for $\pi^0 \rightarrow \gamma A' \ A \rightarrow \chi \chi$ at NA62

- Search for $K^\pm \rightarrow \pi^\pm \pi^0 \rightarrow \pi^\pm \gamma A' \rightarrow \pi^\pm \gamma \chi \chi$ searching for $\pi^\pm$ one $\gamma$ and $M_{\text{miss}}$
  - Assuming $\text{BR}(A' \rightarrow \chi \chi)=1$

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

- Mass reach bounded from above to $\pi^0$ mass ($\sim 135$ MeV)
  - Strong kinematic suppression near the mass limit

- Search for a peak in the missing mass $M_{\text{miss}}^2 = (P_K - P_{\pi} - P_\gamma)^2$

- Extraction of limits comparing to $\text{BR}(\pi^0 \rightarrow \gamma \gamma)$

$$\frac{n_{\text{sig}}}{n_{\pi^0}} = \frac{\text{BR}(\pi^0 \rightarrow A' \gamma)}{\text{BR}(\pi^0 \rightarrow \gamma \gamma)} \epsilon_{\text{sel}} \epsilon_{\text{trg}} \epsilon_{\text{mass}}$$

$$\frac{\text{BR}(\pi^0 \rightarrow \gamma A')}{\text{BR}(\pi^0 \rightarrow \gamma \gamma)} \approx 2\epsilon^2 \left| F(M_{A'}^2) \right|^2 \left( 1 - \frac{M_{A'}^2}{M_{\pi}^2} \right)^3$$
Data-driven BG estimate (peak resolution mostly left-right-symmetric)

Limited amount of statistics used $1.5 \times 10^{10} K^+$ (6.5% of 2016 sample).

Promising preliminary limit at 90% CL on invisible A' decay.
Dark photon in $K^\pm \rightarrow \pi^\pm A' A' \rightarrow \ell^+ \ell^-$
Dark photon in $K^\pm \rightarrow \pi^\pm A'$ $A' \rightarrow \ell^+\ell^-$

- Mixing from $K \rightarrow \pi^\pm \gamma^*$ with $\gamma^*$ mixing to $A'$

$$\Gamma_{K \rightarrow \pi V} = \frac{\alpha K^2}{210 \pi^4} \frac{m_V^2 W^2}{m_K^2} f(m_V, m_K, m_\pi) \implies \text{Br}_{K \rightarrow \pi V} \approx 8 \times 10^{-5} \times \kappa^2 \left(\frac{m_V}{100 \text{ MeV}}\right)^2.$$  

- Depending on $A'$ the decay type can end up in different final states similar to kaon decays:
  - Visible: $K \rightarrow \pi^\pm e^+e^-$ can hide $K \rightarrow \pi^\pm A'$ $A' \rightarrow e^+e^-$
  - Visible: $K \rightarrow \pi^\pm \mu^+\mu^-$ can hide $K \rightarrow \pi^\pm A'$ $A' \rightarrow \mu^+\mu^-$
  - Invisible: $K \rightarrow \pi^\pm \nu\nu$ can hide $K \rightarrow \pi^\pm A'$ $A' \rightarrow \chi\chi$

- All of this mode are accessible in NA48/2+NA62 experiments!

- Signature being narrow mass peak in $\ell^+\ell^-$ invariant mass or $M_{\text{Miss}}$
NA48/2 search for $K^\pm \rightarrow \pi^\pm \mu^\pm \mu^\mp$

- NA48/2 search resonances in decays $K^\pm \rightarrow \pi^\pm \mu^\pm \mu^\mp$:
  - Sample of $2 \times 10^{11} K^\pm$ decays collected in 2003–04.
  - Can be reinterpreted as: $K^\pm \rightarrow \pi^\pm A' \ A' \rightarrow \mu^\pm \mu^\mp$
  - Limits on $\text{BR}(K^\pm \rightarrow \pi^\pm A')\text{BR}(A' \rightarrow \mu^\pm \mu^\mp)$ in the mass region:
    - $210 \text{ MeV} < M_{A'} < 350 \text{ MeV}$ as function of the lifetime
    - $A'$ lifetime $<10^{-12}$ for explored region ($\varepsilon^2 < 10^{-5}$)
    - Upper Limit on $\text{BR}(K^\pm \rightarrow \pi^\pm X)\text{BR}(X \rightarrow \mu^\pm \mu^\mp)$ in $10^{-9} - 10^{-10}$ region

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NA48/2 $K^\pm \rightarrow \pi^\pm \mu^\pm \mu^\mp$ and A’ bounds

\[ UL(\varepsilon^2) = \frac{UL(BR(K^\pm \rightarrow \pi^\pm X)BR(X \rightarrow \mu^\pm \mu^\mp))}{BR(K^\pm \rightarrow \pi^\pm X)BR(X \rightarrow \mu^\pm \mu^\mp)} \]

\[ \Gamma_{K \rightarrow \pi V} = \frac{\alpha \kappa^2}{2^{10} \pi^4} \frac{m_V^2 W^2}{m_K^2} f(m_V, m_K, m_\pi) \rightarrow \]

\[ Br_{K \rightarrow \pi V} \simeq 8 \times 10^{-5} \times \kappa^2 \left( \frac{m_V}{100 \text{ MeV}} \right)^2 . \]

\[ Br(X \rightarrow \mu^\pm \mu^\mp) = \frac{r(\mu^\pm \mu^\mp)}{r(\mu^\pm \mu^\mp) + r(e^\pm e^\pm)} \sim 0.5 \]

- Bound in the A’ parameter space not competitive with Babar in the kinetic mixing scenario
  - Universal lepton coupling

- What about if we modify couplings to leptons ($L_\mu$-$L_\tau$)?
  - Muon dominated coupling factor 2 more stringent limit $\sim 5 \times 10^{-6}$
$K^+ \rightarrow \pi^+ \nu \nu$ and the $A'$ invisible decays

In models assuming that the dark photon couples to SM through kinetic mixing $\epsilon \neq 0$, $K^\pm \rightarrow \pi^\pm \nu \nu$ can be used to constrain $K^\pm \rightarrow \pi^\pm A' A' \rightarrow \chi \chi$:

$$\Gamma(K^\pm \rightarrow \pi^\pm Z_d) = \frac{e^2 \alpha W^2 m_{Z_d}^2}{2^{10} \pi^4 m_{K}^2} \sqrt{\lambda(m_{K}^2, m_{\pi}^2, m_{Z_d}^2)}$$

$$\times \left[ (m_{K}^2 - m_{\pi}^2)^2 - m_{Z_d}^2 (2m_{K}^2 + 2m_{\pi}^2 - m_{Z_d}^2) \right],$$

Depending on how the model is built the limit can change significantly for example allowing the mass mixing with SM Z.

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NA48/2 $K^\pm \rightarrow \mu^\pm \nu e^+e^-$ decay

- Can exchange the radiated $\gamma^*$ with $A'$ decaying in $e^+e^-$
  - $K^\pm \rightarrow \mu^\pm \nu A'$ with $A' \rightarrow e^+e^-$
  - $M_{ee}$ spectrum can be searched for $M_{ee}$ resonance (in progress)
  - Measured limits on $BR(M_{A'}) \times 10^{-8}-10^{-9}$ range
  - No need for coupling to electrons! Can explore $A'$ coupling to only $\mu$ models!

- Can exchange the radiated $\gamma^*$ with scalar $\phi$ decaying in $e^+e^-$
  - Enhanced expected wrt by the coupling to $m_\mu^2$
  - Batell, Lange, McKeen, Pospelov, Ritz ArXiv 1606.04943v1

Muon dominated couplings?

Model A: Mass proportionality, $g_\ell \propto m_\ell$. In particular, it implies that the couplings between the scalar $S$ and electrons are 200 times smaller than those with muons. Despite this, the dominant decay channel for $S$ below the di-muon threshold is $S \rightarrow e^+e^-$. 

Model B: Coupling exclusively to muons, $g_\mu > 0$ and $g_e = g_\tau = 0$.

$K^+ \rightarrow \pi^+\mu^+\mu^-$ needs quark related production mechanism.

$K^\pm \rightarrow \mu^\pm \nu \mu^\mp$ is also very interesting in this scenario pure muon coupling!
Recent results on dark sector search

- **Search for Heavy Neutrinos in $K^+ \rightarrow \mu^+ \nu$ Decays.**
  - ArXiv 1705.07510v1
  - Can be recast as $K^+ \rightarrow \mu^+ \nu A'$ with $A' \rightarrow \chi \chi$

- **Searches for lepton number violation and resonances in $K^{\pm} \rightarrow \pi^{\pm} \mu^+ \mu^-$ decays**
  - Can be recast as $K^+ \rightarrow \pi^+ A'$ with $A' \rightarrow \mu^+ \mu^-$

- **Model independent measurement of the leptonic kaon decay $K^{\pm} \rightarrow \mu^{\pm} e^+ e^-$ with the NA48/2 experiment**
  - PoS ICHEP2016 (2016) 636
  - Can be recast as $K^+ \rightarrow \mu^+ \nu A'$ with $A' \rightarrow e^+ e^-$

- **Search for the dark photon in $\pi^0$ decays**
Conclusions

- **NA48/2** set a limit on the $A'$ decays to $e^+e^-$ (PLB746 (2015) 178)
  - Improvement of the existing limits for visible decays in the range 9-70 MeV/c².
  - Assuming **kinetic mixing** and dark photon **decaying to lepton pairs only** the whole favored by $(g-2)_\mu$ region has been excluded

- **NA48/2** limit on $A'$ decays to $K^\pm\rightarrow\pi^\pm X \ X\rightarrow\mu^+\mu^-$ (PLB 769 (2017) 67–76)
  - The limit is not competitive as bound on kinetic mixing models
  - Being the only one in the region 210-350 MeV not obtained with electrons can be relevant in non universal coupling models.

- **NA62** is able to investigate dark sector physics in kaon decays
  - Advanced analysis of $K^\pm\rightarrow\pi^\pm\pi^0 \ \pi^0\rightarrow\gamma A' \ A'\rightarrow\chi\chi$ for invisible $A'$ decays
  - Decays of $K^\pm\rightarrow\pi^\pm X \ X\rightarrow\mu^+\mu^-$ and $X\rightarrow\chi\chi$
  - Dark sector search in Dump more also very promising ($A'$, ALPs HNL)
  - NA62 implemented a dedicated di-lepton trigger for dark sectors studies!

**Kaons are an exiting field to search for dark sectors candidates!**
The Be$^8$ anomaly and the proto-phobic fifth force

**PRL 116, 042501 (2016)**

<table>
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<tr>
<th>$p^+$</th>
<th>$7\text{Li}$</th>
<th>$A$</th>
<th>$^8\text{Be}$</th>
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$\pi^0$-phobia $=$ $p^+$-phobia

To avoid NA48/2, prohibit $\pi^0$ decay to $X\gamma$

$$\pi^0 \rightarrow \gamma X$$

FROM QUARK CONTENT

$$Q_u Q'_u - Q_d Q'_d = 0 \quad Q'_d = -2Q'_u$$

ProtoPhobic coupling