Search for production of an invisible dark photon from $\pi^0$ decays at NA62

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Rencontres de Moriond QCD and High Energy Interactions

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With LHC a large new territory has been explored and no unambiguous signal of New Physics has been found at TeV scale.

From Cosmological and Astrophysical observations something else than ordinary Baryonic matter should exist. The abundance of this new entity is 5 times larger than SM particles.

An attractive possibility: the unresolved problems could be explained by NP, below the EW scale, feebly interacting with SM → intensity frontier experiment.

What about introducing a new force? Interaction between DM and SM mediated by these new Gauge-invariant operators.
Hidden sector motivations

- Many possible dynamics: vector ($A'$ dark photon), neutrino (HNL), axial (ALP a), scalar.
  The simplest hidden sector model introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or $A'$ boson [B. Holdom Phys.Lett. B166 (1986) 196]

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

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

- Various experimental hints for hidden sector at MeV-GeV, e.g., $a_\mu$ 3.5-σ discrepancy:
  Might be due to a Dark photon $A'$...
Dark photon in $\pi^0$ decays

- A consequence of this interaction is the transition $\pi^0 \rightarrow \gamma A'$ [Batell, Pospelov and Ritz, PRD 80, 095024 (2009)]:

\[
\begin{align*}
\pi^0 & \rightarrow \gamma A' \\
\gamma & \rightarrow \gamma \\
\gamma & \rightarrow \gamma \\
\gamma & \rightarrow \gamma \\
\gamma & \rightarrow \gamma
\end{align*}
\]

\[
\frac{BR(\pi^0 \rightarrow \gamma A')}{BR(\pi^0 \rightarrow \gamma \gamma)} = 2\varepsilon^2 \left(1 - \frac{M_{A'}^2}{M_{\pi^0}^2}\right)^3
\]

- Identify a solid source of $\pi^0$:
  - @ colliders: $e^+e^- \rightarrow \rho, \eta, \phi$
  - @ fixed target experiments in target production (background from beam-target interaction)
  - @ fixed target experiments using a cascade process, where the $\pi^0$ is one of the products:

\[
K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow \gamma A'
\]

A kaon factory with high-frequency tracking of beam particles, redundant PID, high-efficiency photon vetoes would be suitable for this search.
NA62: the CERN kaon factory

Kaon physics at CERN:
✓ Fixed target experiments at CERN SPS
✓ Kaon decay-in-flight

Currently in NA62:
~200 participants
29 institutions from 13 countries

Main goal: \( \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \) measurement with \( \mathcal{O}(10\%) \) precision

SM prediction: \( \text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11} \)  
SPS protons:
400 GeV/c
$10^{12}$ PoT/sec on spill
4.8 sec spill
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Secondary beam:
- 75 GeV/c, 1% bite
- 100 μrad
- $60 \times 30$ mm$^2$
- $K^+(6\%)/\pi^+(70\%)/p(24\%)$
- 750 MHz at GTK3

[NA62 Detector Paper, JINST 12 (2017), P05025]
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Kaon decay region:  
60 m  
$\sim 5$ MHz  
$O(10^{-6})$ mbar
Performances

- Excellent time resolution $\mathcal{O}(100 \text{ ps})$ to match beam and daughter particle information
- Kinematics: rejection of main $K$ modes $10^4$ via kinematics reconstruction
- PID capability: $\mu$ vs $\pi$ rejection of $O(10^7)$ for $15 < p(\pi^+) < 35$ GeV
- High-efficiency veto: $10^8$ rejection of $\pi^0$ for $E(\pi^0) > 40$ GeV
Invisible decay of massive $A'$ or long lived massive $A'$ hypothesis. Two trigger lines used.

- **Minimum-bias** - To count $n_{\pi^0}$ produced from $K^+ \rightarrow \pi^+\pi^0$: $K^+, \pi^+ - \text{ID}$ and $(P_K - P_\pi)^2$ around $M^2_{\pi^0}$ (normalization-sample).

- **Signal-trigger** – Additional conditions to enforce the sole presence of a $\pi^+$ and one $\gamma$ on LKr in the final state: photon veto, missing momentum pointing towards LKr, CHOD extra-activity veto (signal-sample).
Analysis principle

- In the signal-sample a peak search in $M_{\text{miss}}^2 = (P_K - P_\pi - P_\gamma)^2$ distribution is performed. A sliding $M_{\text{miss}}^2$ window ($\pm 1\sigma_{M_{\text{miss}}^2}$) is used to count $n_{\text{sig}}$ for different $A'$ mass hypothesis.

- From $n_{\text{sig}}$ to the coupling $\varepsilon^2$ with the master formula:

$$BR(\pi^0 \rightarrow \gamma A') = BR(\pi^0 \rightarrow \gamma \gamma) \frac{n_{\text{sig}}}{n_{\pi^0} \varepsilon_{\text{trg}} \varepsilon_{\text{sel}} \varepsilon_{\text{mass}}}$$
Most abundant background due to $\pi^0 \rightarrow \gamma\gamma$ with one $\gamma$ not detected.

Data-driven approach to evaluate background: same cuts of the signal-sample but the CHOD extra-activity veto. This ensures the selection of $\pi^0 \rightarrow \gamma\gamma$ events with one $\gamma$ lost because of conversion upstream of the CHOD.

No assumption on the shape of the tail of the $M_{\text{miss}}^2$ spectrum and no analytical extrapolation of the background; no use is made of the data signal-sample.
Background evaluation

The background sample is scaled to the signal sample in a side-band region adjacent to but not overlapping with the $A'$ search region: $0.00005 < M_{\text{miss}}^2 < 0.00075 \text{ GeV}^2/c^4$

The $A'$ search region is $0.00075 < M_{\text{miss}}^2 < 0.01765 \text{ GeV}^2/c^4$ for all the mass hypotheses (30-130 MeV/c²). $O(1)$ background events in the tail with $n_{\pi^0} \approx 4 \times 10^8$ selected.
Results from NA62 2016 data

- CLs technique using a subsample of 2016 data, corresponding to 1% of the statistics collected by NA62 in 2016–2018

- No statistically significant excess is detected: observed upper limits @ 90% CL compatible with fluctuations from the background-only hypothesis

![Graph showing results](image)

Results from NA62 2016 data

- Improvements on the previous limits over the mass range 60–110 MeV/c² (also on the model-dependent limit from E787/E949 experiments in all scenarios)

- New experimental technique: models involving suppressed lepton couplings might produce a signal at NA62 notwithstanding other experimental results.
Conclusions

✓ NA62 took data with the complete detector in 2016-2018.

✓ Exploiting the efficient photon-veto capability and high resolution tracking of the NA62 detector, a search for an invisible massive dark photon $A'$ is performed. No $A'$ signal is observed, improving on the previous limits over the mass range 60–110 MeV/c$^2$ (CERN-EP-2019-048, arxiv:1903.08767)

✓ With slight modifications to the analysis, a search is conducted for the $\pi^0 \rightarrow \gamma \nu \overline{\nu}$ whose BR$\approx10^{-18}$ within the SM. An upper limit is set, BR$<1.9\times10^{-7}$ at 90% CL, improving the current limit by more than three orders of magnitude

✓ Different production modes/signals of $A'$ can be studied at NA62: search for visible decays to SM particles (production at target/dump)
  • Production from primary beam secondaries: $pN \rightarrow X\pi^0$, $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow l^+l^-$
  • Production from primary beam: $pN \rightarrow XA'$, $\rightarrow A' \rightarrow l^+l^-$
Backup
Results from NA62 2016 data

- $A'$ signal at 80 MeV/$c^2$ added to data collected with different values of $\varepsilon^2$ taking into account the full selection and trigger efficiency with its uncertainty.
- Statistical treatment applied to the signal-injected samples to prove the discovery sensitivity of the analysis.

![Graph showing results from NA62 2016 data](image)
$M_{\text{miss}}^2$ window for the peak search

- To check the MC $\sigma_{M_{\text{miss}}^2}$, $\pi^0$ Dalitz decay is used

$$K^+ \rightarrow \pi^+ \pi^0, \pi^0 \rightarrow e^+ e^\gamma$$

The di-lepton system mimics the $A'$ behavior in the $\pi^0$ decay. Dalitz selection implemented and applied both to data and MC Dalitz sample

- Data Dalitz
- MC Dalitz fully reconstructed
- MC Dalitz with di-lepton momentum from MCtruth

- Resolution can be computed as a function of di-lepton mass and compared with the $\sigma_{M_{\text{miss}}^2}$ as function of the $A'$ mass (agreement within ~10%).
The signal window has been varied to $\pm 0.9$ and $1.1 \sigma_{M^2_{\text{miss}}}$

The signal window has been varied to $\pm 2\sigma_{M^2_{\text{miss}}}$
The lower edge of the window used to evaluate the scale factors to compare background and signal-search samples has been varied using the following additional values: -0.00015, 0.00015, 0.00025 GeV²/c⁴.

The extent of the “flat region” has been varied by moving its lower edge to 0.004 and 0.006 GeV²/c⁴.