Search for invisible dark photon at NA62

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on behalf of the NA62 collaboration
Hidden sector searches: motivations

If DM is a thermal relic from hot early universe, can hunt for it in particle-physics: search for non-gravitational interactions DM-SM

Mediators of a hidden sector might exist, inducing DM-SM field (feeble) interactions many possible dynamics: vector ($A'$, aka dark photon), neutrino (HNL), axial (ALP, $a$), Higgs..

Various experimental hints for hidden sector at MeV-GeV: e.g., muon $g$-2

Feeble interaction:
- suppressed production rate, long-lived states
- fully profit of a high-intensity setup

Dark photon models

Model freedom, e.g. a vector $X$ with coupling $g_X x_f$ to SM fermions $f + a$ hidden sector

$$\mathcal{L} \subset g_X \sum_f x_f \bar{f} \gamma^\mu f X_{\mu} + \sum_\chi \mathcal{L}_{X\chi\bar{\chi}}$$

In the minimal $A'$ scenario:
- kinetic mixing with photon: $g_X = \varepsilon e$, $x_l = -1$, $x_\nu = 0$, $x_u = 2/3$, $x_d = -1/3$, etc.
- model-dependent mixing with $Z$ weak current

If $M_X > 2 M_\chi$ for some $\chi \rightarrow$ sizeable invisible width

Model freedom (e.g.: $A'$, B-L, B, proto-phobic, etc.) $\rightarrow$ be experimentally-driven
NA62: a high-intensity setup

High-intensity proton-produced charged hadron beam:

$10^{12}$ 400-GeV protons/s from $\sim$3.5-s SPS spills onto a Be target

Secondary 75-GeV beam selected: 1% momentum bite, X,Y divergence $< 100 \mu$rad

Can track 750 MHz beam (6% $K^+$) and sustain $\sim$5 MHz $K^+$ decay in a 60-m long volume in vacuum

Kinematics, rejection of main K modes $10^4$—$10^5$ via kinematic reconstruction

PID capability, $\mu$ vs $\pi$ rejection of $O(10^7)$ for $15 < p(\pi^+) < 35$ GeV

High-efficiency veto of additional photons, $O(10^8)$ rejection of $\pi^0$'s for $E(\pi^0) > 40$ GeV

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International conference on Kaon physics - Perugia (Italy)
NA62: a high-intensity setup
Search for dark photon in $\pi^0 \rightarrow \gamma$ invisible

Tag a pure, intense $\pi^0$ beam of known momentum from $K^+ \rightarrow \pi^+\pi^0$ decays

Contamination $< 10^{-3}$ solely reconstructing $K^+ \rightarrow \pi^+$ decays + missing mass condition

In the $A'$ model:

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

Signal signature: $\pi^0$ tagging, one photon + missing momentum, no further activity

Signal trigger based on “1 track” + small forward energy $\leftarrow$ same trigger line as $\pi\nu\nu$

Normalization based on minimum-bias triggered $\pi^0$-tagged events, $n_{\pi^0}$

$$\text{BR}(\pi^0 \rightarrow A'\gamma) = \text{BR}(\pi^0 \rightarrow \gamma\gamma) \frac{n_{\text{sig}}}{n_{\pi^0}} \frac{1}{\epsilon_{\text{sel}}\epsilon_{\text{trg}}\epsilon_{\text{mass}}}$$

The efficiency for $\pi^0$ tagging cancels at first order
Search for dark photon in $\pi^0 \rightarrow \gamma$ invisible

Normalization based on minimum-bias triggered $K^+ \rightarrow \pi^+\pi^0$ decays selected as “$K_{2\pi}$”:

A single $K^+-\pi^+$ vertex with

- position $115 < z < 165$ m downstream the T10 target
- $15 < p_\pi < 35$ GeV/$c$, thus ensuring at least $\sim 40$ GeV of missing energy
- $0.013 < (P_K-P_\pi)^2 < 0.023$ GeV$^2$/c$^4$, compatible with $\pi^0$ mass to within $\sim \pm 20$ MeV

No conditions on $\pi^0$ photons

Contamination < $10^{-3}$

Data from 2016, $n_{\pi^0} \sim 412$ M $\pi^0$s tagged from $K_{2\pi}$ decays ($\sim 1\%$ of full data set)
Selection criteria for $\pi^0 \rightarrow \gamma$ invisible

Signal search starts from $K_{2\pi}$ selected ($\pi^0$ tagged) events:

One photon in LKr, missing momentum pointing to LKr, isolation condition, minimum $E_{\text{miss}}$

Veto on additional particles using CHOD, LAVs-IRC-SAC, RICH, LKr

Photon detection efficiencies:

- LAVs $\mathcal{O}(10^{-3})$ for $E_\gamma$ in 1—4 GeV
  $< 10^{-3}$ for $E_\gamma > 4$ GeV
- LKr $\mathcal{O}(10^{-4})$ for $E_\gamma$ in 10—20 GeV
  $< 10^{-5}$ for $E_\gamma > 20$ GeV
- IRC $< 10^{-3}$ for $E_\gamma > 10$ GeV
- SAC $\mathcal{O}(10^{-3})$ for $E_\gamma > 10$ GeV
Search for $\pi^0 \rightarrow \gamma$ invisible

Search for a peak around $M_{A'}^2$ from $M_{\text{miss}}^2 = (p_K - p_{\pi^+} - p_\gamma)^2$

Signal $M_{\text{miss}}^2$ resolution $6\times10^{-4}$ GeV$^2$/c$^4$ for $M_{A'}$ in $30-130$ MeV/c$^2$ \[ \leftarrow \] Search region

Perform a counting experiment in $\pm 1\sigma$ sliding $M_{\text{miss}}^2$ windows

$\pi^0 \rightarrow \gamma\gamma$ background artificially enhanced
Background to $\pi^0 \rightarrow \gamma$ invisible

Dominant background: $\pi^0 \rightarrow \gamma\gamma$ with 1 photon missing, reduced by $\sim 10^{-4} - 10^{-5}$ by $\gamma$-vetoes

Inefficiency dominated by photon conversions upstream the LKr

Data-driven background evaluation by inverting CHOD-based veto conditions

Background normalized to data in side-band region (A’ excluded by past experiments)
Signal region for $\pi^0 \rightarrow \gamma$ invisible

Compare observed counts to expected background in the signal region, $30 < M_{A'} < 120$ MeV/$c^2$

From a sample of $4 \times 10^8 \pi^0$'s, background at $O(1)$ event for $M_{A'} > 60$ MeV/$c^2$
Result for $\pi^0 \rightarrow \gamma \text{ invisible}$

Compare observed event counts to expected background: CLs method, counting experiment

Observation compatible with expected fluctuations of pure background $\rightarrow$ set 90%CL UL
Implications for $A'$ dark-photon model

Interplay of results from different techniques: $e^+e^- \rightarrow \gamma A'$ [BaBar], $e^-$ dump + $E_{\text{miss}}$ [NA64]

Published most stringent exclusion for $60 < M_{A'} < 110$ MeV/$c^2$
Implications for $A'$ dark-photon model

Interplay of results from different techniques: $e^+e^- \rightarrow \gamma A'$ [BaBar], $e^-$ dump + $E_{\text{miss}}$ [NA64]

Published most stringent exclusion for $60 < M_{A'} < 110 \text{ MeV/c}^2$, covered by new NA64 result

Same plot holds for dark photon coupled to B-L current if $\varepsilon e \rightarrow g_{B-L}$
and for B-current-coupled dark-photon

Different scenario for dark photon coupled to Baryonic current [see PRL 119 (2017) 141803]

NA64, BaBar, Belle-II production processes suppressed by $\alpha^2/4\pi^2$

$g_B$

$10^{-2}$

$10^{-4}$

$10^{-6}$

$10^{-8}$

$10^1$ $10^2$ $10^3$ $10^4$ $10^5$ $10^6$ $10^7$ $10^8$

$M_{A'} [\text{MeV}/c^2]$
Conclusions and outlook

A first search for an invisible particle in $\pi^0 \to A' \gamma$ has been presented
Competitive limits on $A'$, B-L dark photon models by using \(~1\%\) of NA62 data set
Models with unsuppressed FCNCs (e.g. B-model) dominated by $K \to \pi\nu\bar{\nu}$

Analysis by-product: search for $\pi^0 \to \gamma\nu\bar{\nu}$ decay (SM expected BR $\sim 10^{-18}$):
BR $< 1.9\times10^{-7}$@90% CL, improving x1000 over previous results

Perspectives from analysis of full NA62 data set:
Expected yield increase by O(100)
Background to be kept under control $\to$ possible through kinematic fitting
Spare slides
Systematic checks: discovery potential

Signal with $M_{A'} = 80$ MeV/c$^2$ and various $\varepsilon^2$ values added to data

Account for full selection and trigger efficiency with related uncertainties