Dark photon search with neutral meson decays at the PHENIX experiment


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Introduction

Composition of our universe

- Only 5% from ordinary matter, 27% dark matter & 68% dark energy
  - Supported by:
    1. Gravitational lensing
    2. CMB fluctuations

→ Fundamental question: What is dark matter?
  - Long list of candidates (WIMP, Axion, SUSY, ...)

New possibility – dark sector

a. Extension of the Standard Model (SM)
b. Additional new gauge field - **Dark photon**
  - Motivated by experimental results can not be described by SM
Possible BSM phenomena

Beyond Standard Model (BSM) phenomena

✧ Dark photon models are strongly motivated by:
  1. Positron fraction in cosmic rays
     ✗ Excess over the SM prediction (PAMELA, AMS-02)
  2. Muon anomalous magnetic moment, \(a_\mu \equiv (g_\mu - 2)/2\)
     ✗ Very precise measurement as well as theory calculations
     ✗ About 3σ deviation from the SM predictions (BNL-E821)

Discrepancy of \(a_\mu\) from SM predictions

\[
\begin{align*}
\text{JN 09 (e^+e^-)-based) } & \quad -301 \pm 65 \\
\text{DHMZ 10 (\tau-based) } & \quad -197 \pm 54 \\
\text{DHMZ 10 (e^+e^-) } & \quad -289 \pm 49 \\
\text{HLMNT 11 (e^+e^-) } & \quad -263 \pm 49 \\
\text{BNL-E821 (world average) } & \quad 0 \pm 63
\end{align*}
\]

An alternate interpretation is that \(\Delta a_\mu\) may be a new physics signal with supersymmetric particle loops as the leading candidate explanation. Such a scenario is quite natural, since...
Dark photon

Simplest dark photon scenario
◇ Introduction of an additional $U(1)$ gauge symmetry
  ✓ Gauge boson = dark photon referred to as $U$ (also $A'$ or $Z_d'$)
  ✓ Communication with SM through a small mixing on the kinetic term of the QED Lagrangian
    \[ \mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2} F_{\mu\nu}^{\text{QED}} F_{\mu\nu}^{\text{dark}} \]
  ✓ Mixing with ordinary photons in all processes

Mapping in parameter space
◇ Situation about 1 year ago
  ✓ Theory curves from Hye-Sung Lee & Bill Marciano

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**Dark photon**

**Simplest dark photon scenario**

✧ Introduction of an additional $U(1)$ gauge symmetry
  
  ✔ Gauge boson = dark photon referred to as $U$ (also $A'$ or $Z_d'$)
  
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  ✔ Mixing with ordinary photons in all processes

**Mapping in parameter space**

✧ Situation about 1 year ago
  
  ✔ Theory curves from Hye-Sung Lee & Bill Marciano
  
  ✔ Uncovered region in 30-50MeV for the muon $g$-$2$ explainable band with 90% CL
  
  → **Strong motivation for our measurement**
Search in $\pi^0/\eta$ Dalitz decays

Assumption: Dark photon exclusively decays into $e^+e^-$ pair.
- Its natural width is very narrow.
  - Expected peak width = detector mass resolution
- Similar approach with COSY-WASA, HADES, NA48/2

Important requirements for this measurement
1. Large statistics of $e^+e^-$ from $\pi^0/\eta$ Dalitz decays
2. Good mass resolution of $e^+e^-$
PHENIX experiment at RHIC

✧ Relativistic Heavy Ion Collider at BNL
  ✓ Collision species: p+p, d+Au, Au+Au, Cu+Cu, U+U, ...
  ✓ Maximum collision energy: 200 (for HI), 500 (for p+p) GeV
  ✓ Running since 2001

✧ PHENIX experiment
  ✓ Originally designed for the study of Quark Gluon Plasma
  ✓ One of two major experiments at RHIC
**e^+e^-** measurement at PHENIX

- Material budget before DC: 0.39% $X_0$ for 2006 & 2008 runs
- 2009 run w/ Hadron Blind Detector (additional 2.4% $X_0$)

**e^+e^-** measurement in $|\eta|<0.35$, 2×90° in $\phi$
- Tracking: Drift Chamber & Pad Chamber
  - $\delta p/p=1\% \oplus 1.1\% \times p$ [GeV/c]
- Electron trigger & ID: RICH & EMCal (E-p matching)
  - Hadron rejection $>10^3$
Background subtraction

Unphysical background pairs

✧ Evaluation of the following BG contributions using $e^+e^+$ & $e^-e^-$ pairs
  a. Combinatorial pairs between totally uncorrelated electrons
  b. Jet pairs: electrons from hadrons in the same or back-to-back jets
  c. Cross pairs: fake pairs from decays with $2e^+e^-$ in a final state

✧ Sum of Background contributions < 10% in $m_{ee}$<100MeV for $e^+e^-$
Correlated $e^+e^-$ mass spectra after BG subtraction

- 700k (p+p) + 1.0M (d+Au) = total 1.7M $e^+e^-$ from $\pi^0/\eta$ Dalitz decays
- Described well by a “cocktail” of known hadron decays + BG
- No significant dark photon peak visible
- A statistical test to extract a possible dark photon signal behind a huge amount of $e^+e^-$ from Dalitz decays
CHAPTER 2. ANALYSIS

2.4.2 Determination of the Dalitz continuum yield

The Dalitz continuum yield is determined by fitting to the data with a reasonable function. The fit function is based on the Kroll-Wada formula which essentially describes the Dalitz continuum distribution of hadrons. Additionally, the Chebychev polynomial is combined with the Kroll-Wada formula to take into account for a distortion of the mass shape due to an acceptance as:

\[
f_{fit}(m_{ee}) = \frac{1}{m_{ee}} \times \left[ \left( 1 - \frac{m_{ee}^2}{m_{\pi^0}^2} \right)^3 + r_{\eta/\pi^0} \cdot \left( 1 - \frac{m_{ee}^2}{m_{\eta}^2} \right)^3 \right] \times f_{chebychev}(m_{ee}),
\]

\( f_{chebychev}(m_{ee}) \)

Common fit function for the data sets with different scale factors

- Chebychev polynomial allows for a slight deviation from Kroll-Wada shape due to detector effects.

- Two separate fit ranges to avoid having a local bad \( \chi^2 \)
  - Smoothly connecting at the break-point
Dark photon event limits

CLs approach

 shm Calculate relative likelihoods of how well the data is described by:
1. Only Dalitz background
2. Dark photon signal + Dalitz background
   ✔ Peak width = 3.1MeV dominated by detector resolution

 shm Upper limits of dark photon candidates with 90% CL
 ✔ Experimental sensitivity with ±1,2σ uncertainties are shown.
 ✔ Observed limits within the 2σ fluctuation of our sensitivity
 → No dark photon signal was observed.
Translation into limits in $m_U - \varepsilon^2$ space

- $\varepsilon^2 = \frac{2 \alpha_{EM} \sigma}{3 \pi m_U} \sqrt{2\pi} R(m_U)$
- $R(m_U) = N_U(m_U)/N_{Dalitz}(m_U)$

Upper limits in 30-90MeV

- Stricter than KLOE, WASA, HADES, A1
- Combining with BaBar, the muon g-2 explainable band is almost ruled out.

→ Completely excluded by NA48/2 recently (arXiv: 1504.0607)
Summary

- Dark photon search was performed through $\pi^0/\eta$ Dalitz decays at PHENIX
  - Analyzed 1.7M pairs in 2006-2009 data
  - No dark photon signal was observed.
  - Combining with the other experimental results, dark photon is ruled out as the explanation for measured $a_\mu$ anomaly.

Outlook

- Further analysis with the recent high luminosity data and a silicon vertex detector