Search for invisible decay of a dark photon in $e^+e^-$ collisions at BABAR

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XVI Incontri di Fisica della Alte Energie
Trieste, 19 – 21 Aprile, 2017
Motivation

• With the $\sim 125$ GeV/c$^2$ Higgs scalar, the Standard Model (SM) particle contents might be complete.

• However, big Beyond Standard Model (BSM) questions remain:
  – Dark matter, Neutrino masses, Baryon Asymmetry in the Universe, Inflation, Dark Energy

• There are intriguing astrophysical observations: Pamela, Fermi, AMS2, Dama...

Could there be a hidden sector at low energy?

• A flurry of models include: SUSY models, portals/new effective scales:
  – Vector, Scalar, Neutrino, axion-like…

• An emerging experimental field at accelerators (colliders, beam dumps)

➢ Today: new preliminary results from BABAR at PEP-II

• Search for a dark photon decaying invisibly
  
arXiv:1702.03327
**BABAR detector and collected data sample**

**DIRC**
144 quartz bars.
11000 PMTs

**1.5 T Superconducting Solenoid**

**ElectroMagnetic Calorimeter**
6580 CsI(Tl) crystals

**Drift Chamber**
40 layers

**Silicon Vertex Tracker**
5 layers, double-sided strips

**Intrumented Flux Return**
RPC/LS. Muons + neutral hadrons

**BABAR recorded luminosity and data set (1999-2008):**

- **$\Upsilon(4S)$:** 480 fb$^{-1}$
- **$\Upsilon(3S)$:** 630 fb$^{-1}$
- **$\Upsilon(2S)$:** 460 fb$^{-1}$

**Details in:**
- NIM A479, 1 (2002),
- NIM A729, 615 (2013)
Dark photon $A'$

- Dark matter models introducing a new sector with a “dark” force mediated by a light gauge boson can accommodate anomalies observed in astrophysical research

\[ \chi \chi \rightarrow A'A' \rightarrow (e^+e^-)(e^+e^-) \]

$m_\chi \sim \text{TeV}$; $m_{A'} \sim \text{MeV-GeV}$

Arkani-Hamed et al. PRD 79, 015014 (2009)

- Kinetic mixing of $A'$ with SM $\gamma$ (*vector portal*)
  - mixing strength $\varepsilon \approx 10^{-5} - 10^{-2}$
- Dark photon – SM fermions coupling $\alpha' = \varepsilon^2 \alpha$

- $A'$ decay modes depend on its mass and coupling, as well as on particle spectrum of the dark matter
  - if lowest DM state $2m_\chi > m_{A'} \Rightarrow A' \rightarrow \text{SM particles}$ (in particular lepton pairs $A' \rightarrow e^+e^-, \mu^+\mu^-$)
  - if lowest DM state $2m_\chi < m_{A'} \Rightarrow A' \rightarrow \text{invisible}$ is the dominant decay ($A' \rightarrow \chi\chi$)
Searches at BABAR: $e^+e^- \rightarrow \gamma A'$; $A' \rightarrow e^+e^-, \mu^+\mu^-$

In $BABAR$ a dark photon can be produced in

$e^+e^- \rightarrow \gamma A'$; $A' \rightarrow e^+e^-, \mu^+\mu^-$

with a cross section proportional to $\varepsilon^2 = \alpha'/\alpha$

- Analysis performed on the full data sample of 514 fb$^{-1}$
- Look for a narrow peak in the invariant mass of the lepton pair
- Scan the energy range from 20 MeV to 10.2 GeV

Combined UL at 90% C.L. on production cross section

$m_{A'}$(GeV)

- No significant excess observed
- Largest significance 3.4$\sigma$ at 7.02 GeV
After \textit{BABAR} and NA48/2 results the preferred region of phase space to explain the muon g-2 with visible decays of a dark photon is fully ruled out.
Search for single-photon final states:
- assume on-shell $A'$ ($m_\chi < m_{A'}/2$), with negligible decay width w.r.t. experimental resolution
- assume that $A'$ decays predominantly to DM

- The analysis optimized for and interpreted in terms of a dark photon decaying invisibly
- Similar signature for other modes, e.g. axion production, light Higgs boson
  - The recoiling particle can be either a vector or a scalar

**Low-multiplicity final state: photon + nothing else**
- Missing energy and momentum is the best signature
- Hermeticity and efficiency of the detector are the key
- Strategy: select single-photon events, look for a bump in the missing mass or $E_{\gamma}^*$
- Main backgrounds:
  - $e^+e^- \rightarrow \gamma\gamma$: peaking at $M_\chi^2 \sim 0$, hard to predict with simulation
  - $e^+e^- \rightarrow e^+e^-\gamma$: continuum distribution in $M_\chi^2$
  - machine background: do not mimic signal, but can be the second photon in a signal event

\[
E_{\gamma}^* = \frac{s - M_\chi^2}{2\sqrt{s}}
\]
2007 analysis results: $Y(3S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible}$

Preliminary results: arXiv:0808.0017
analysis optimized for search for a light CP-odd Higgs boson $A^0 \rightarrow \text{invisible}$

No significant signal;
limits on BF constrain
NMSSM parameter
space

Results reinterpreted by theorists in terms of other NP scenarios

Unpublished. Nevertheless >90 citations!

R. Essig et al.,
JHEP 1311, 167 (2013)
Search for $A' \rightarrow \text{invisible}$: Trigger

- Two single-photon software trigger algorithms, with different $E_\gamma^*$ threshold, implemented at different times for the final BABAR running period
- Trigger lines further refined by software filters
  - high-energy photon filter line: $E_\gamma^* > 3$ GeV, no tracks with $p^*>1$ GeV/c
    - data set: 53 fb-1, mostly at the Y(3S) and Y (2S), with a small sample at the Y(4S)
  - low-energy photon line: $E_\gamma^* > 1.5$ GeV, no tracks with $p^*>0.1$ GeV/c, loose shower shape
    - data set: a subset of the previous one, with no Y(4S) sample

- This naturally split the selection into two broad $m_{A'}$ ranges
  - low mass (high $E_\gamma^*$): $-4 < m_{A'} < 36$ GeV$^2$
  - high mass (low $E_\gamma^*$): $24 < m_{A'} < 69.0$ GeV$^2$ for the Y(3S) data set
    - $24 < m_{A'} < 63.5$ GeV$^2$ for the Y(2S) data set
Search for $A' \rightarrow \text{invisible}$: Event selection

- Detector hermeticity is a critical issue
- Require $|\cos \theta_{\gamma^*}| < 0.6$ so that both $\gamma$’s are within EMC acceptance
- Still possible that photons escape detection in the EMC
  - azimuthal gaps between crystals aligned with collision point

- $e^+e^- \rightarrow \gamma\gamma$ event with no signal left by second photon in the EMC

- Boosted Decision Tree selector to separate signal and background, based on 12 discriminating variables, including:
  - EMC cluster shape variables $\rightarrow$ photon quality
  - extra detected energy (besides the primary photon) in the LAB system
  - kinematics of the 2$^{nd}$ most-energetic photon, and its angular distance from the primary photon.
  - activity in the IFR around the missing momentum direction (very effective in suppressing the $e^+e^- \rightarrow \gamma\gamma$ background)
- BDT trained separately in Low- and High-mass regions by using 3 fb$^{-1}$ of $Y(3S)$ data, and simulated signal
Search for $A' \rightarrow \text{invisible}$: Fits to data

- Extract signal yields and ultimately set U.L. on $A'$ coupling $\varepsilon$ by simultaneous fits to $M_X^2$ distributions:
  - **High-mass region**: $Y(2S, 3S)$ data, with Loose BDT cut (2 data sets)
    - background dominated by radiative Bhabha, smooth in recoil mass $M_x$
  - **Low-mass region**: $Y(2S, 3S, 4S)$ data, with non-overlapping Loose and Tight selections (6 data sets)
    - both peaking (from $e^+e^- \rightarrow \gamma\gamma$) and smooth background is present

- Perform fits for 166 mass hypothesis

- For each fit:
  - Background PDFs fixed by fitting data in the background region $-0.5< \text{BDT} <0$
  - Signal PDF is a Crystal Ball with parameters fixed from MC
  - Float signal (actually the coupling squared $\varepsilon^2$), and number of background events separately for peaking and continuum
Search for $A' \rightarrow$invisible: Background-only fits

- Example of data in the low-mass region

- Example of data in the high-mass region

- Background-only fits show good agreement with data in all signal regions
Search for $A' \rightarrow \text{invisible}$: Signal extraction

(Local) signal significance vs $m_{A'}$:

$$S = \sqrt{2 \ln \left( \frac{L_{\text{max}}}{L_0} \right)}$$

BABAR Preliminary

- Local (global) significance of $3.1\sigma$ ($2.6\sigma$)
  - global p-value: $\sim 1\%$
  - Slightly smaller fluctuation at $m_{A'} = 5.70$ GeV ($2.8\sigma$)

- No significant signal observed $\Rightarrow$ set U.L. on mixing parameter $\varepsilon$ as a function of dark-photon mass $m_{A'}$

Most significant fit at $m_{A'} = 6.21$ GeV

arXiv:1702.03327
Search for $A' \rightarrow$invisible: Results

• Exclusion regions for invisible decays of a dark photon after BABAR results

• Preferred region to explain $(g-2)_\mu$ entirely excluded

Trieste, 19/04/2017  F. Anulli - Search for invisible decay of a dark photon
Further analyses ongoing or planned

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Conclusions

• Light dark sectors have recently emerged as a possibility for dark matter and provide a rich phenomenology

• *BABAR* pioneered the low-energy, high-intensity collider searches putting stringent limits on the parameter space of various dark sector models
  – Direct searches: unique sensitivity to low-mass new physics in high-statistics datasets
  – Complementary to results from fixed targets experiments and hadron colliders

• *BABAR* searches for invisible decays and for $A' \rightarrow l^+l^-$ excludes the region of parameter space preferred by the $(g-2)_\mu$ value

• More analyses in progress at *BABAR*
Expected reach in the “near” future

LHCb Run 3 (di-muon)

LHCb Run 3 (di-electron)

SHiP

VEPP3

Mu3e

HPS

APEX

Belle II

DarkLight

Mesa

ultimate LHCb reach

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Astrophysical interest


- $\sim$TeV DM: $\chi\chi \rightarrow A'A' \rightarrow (e^+e^-)(e^+e^-)$
- Initial lack of antiproton excess $\rightarrow m_{A'} < \text{few GeV}$
- Possible antiproton excess now observed:

http://www.ams02.org